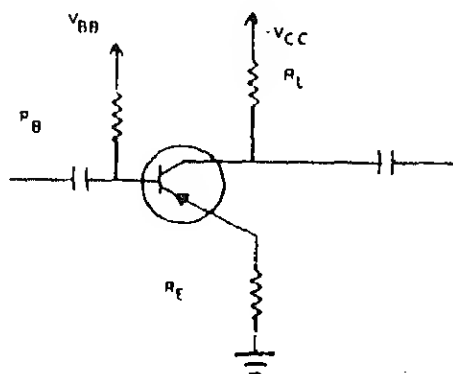


FOR
ADVANCED FIRST-TERM AVIONICS COURSE
CLASS A1
C-100-2010



UNIT II

CNTT-M1704

PREPARED BY
NAVAL AIR TECHNICAL TRAINING CENTER
NAVAL AIR STATION MEMPHIS
MILLINGTON TENNESSEE

PREPARED FOR
CHIEF OF NAVAL TECHNICAL TRAINING

NOVEMBER 1984

FOREWORD

e of this Student's Guide is to assist you in completing "istor Theory," Unit II, of the Advanced First-Term course. The proper use of this guide will increase your knowledge in the above mentioned areas, while building a basis for future training will be built.

of contents lists the page numbers for safety notice sheets, information sheets, and references that will enhance your abilities and skills as an aviation elect

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SAFETY NOTICE

As a Navy electronics technician, you will be required to perform safe and efficient maintenance on various types of electronic equipment. Not only your life, but the lives of many others depend on your being safety conscious at all times. It is the responsibility of all Navy and Marine Corps personnel to prevent accidents. This can be done if everyone develops consistent safety habits and observes all precautions when performing maintenance of any type. Always remember:

SAFETY CANNOT BE OVERSTRESSED!!!!

HOW TO USE THIS STUDENT'S GUIDE

s Guide" has been prepared for you to use while you the Advanced First-Term Avionics Course (Class A1). s been provided for taking notes on the required tion. Remember when you are in class, the informa- vided by your instructor is information you will need your Navy job.

ntains the following:

sheets, containing lesson topic outlines, ns, and ample space for personal notetaking.

n sheets to provide information pertinent to your

arn all you can!

The schedule is as follows:

TOPIC NO.	TYPE	PERIOD	TOPIC
SECOND WEEK			
Fifth Day			
2.1	Class	67 78 79	Series Resonance
2.2	Class	80	Parallel Resonance
THIRD WEEK			
First Day			
2.2	Class	81	Parallel Resonance
2.3	Class	82 83 84	Physics Overview
2.4	Class	85 86 87 88	Semiconductor Physi
Second Day			
2.4	Class	89	Semiconductor Physi
2.5	Lab	90 91	PN Junctions (Labor
2.6	Class	92 93 94 95 96	Junction Transistor

	99	
	100	
Class	101	Biassing Arrangements
	103	
	104	
Class	105	Biassing Arrangements
	106	
	107	
Lab	108	Biassing Arrangements (Laboratory)
	109	
	110	
	111	
	112	
Class	113	Unit/Module Test: Criterion 1
		Written Examination
	114	
	115	
Class	116	Decibels
	117	
Class	118	Feedback Amplifiers
	119	
	120	
Class	121	Feedback Amplifiers
	122	
	123	
Class	124	Direct Coupled and Operational
		Amplifiers
	125	
	126	

		130	
		131	
		132	
2.14	Class	133	Special Device
		134	
		135	
		136	

Third Day

2.14	Class	137	Special Device
		138	
		139	
		140	
2.15	Class	141	Vacuum-Tube Fu
		142	
2.16	Class	143	Triodes
		144	

Fourth Day

2.16	Class	145	Triodes
		146	
		147	
		148	
2.17	Class	149	Multielement
		150	
		151	
		152	

Fifth Day

	Class	153	Unit/Module Test/Written
		154	
		155	
		156	

plete assigned homework may result in disciplinary

Sheet

Period Due

81

89

89

97

97

113

121

129

129

137

145

145

153

153

mathematics, algebra, and trigonometry. A formula trigonometric tables, and a Universal Time Constant be provided. Performance must be in accordance with mathematical principles outlined in Mathematics, Vol. I, 10069 (series), Mathematics, Vol. III, NAVPERS 1007 Basic Electronics, Vol. I, NAVPERS 10087 (series), Electricity, NAVPERS 10086 (series). Performance will be measured by a written multiple-choice examination.

- 2.0 ANALYZE the internal structure and operation of semiconductor junctions by tracing majority and minority current in a given semiconductor device, in accordance with quantum mechanical principles outlined in Basic Electronics NAVPERS 10087 (series) and Aviation Electronics 3 & NAVEDTRA 10317 (series). Performance will be measured by a written multiple-choice examination.
- 3.0 Mathematically ANALYZE the operation of given basic conductor circuits by solving problems in terms of current, reactance, and frequency. A formula sheet will be provided. Responses must be in accordance with Basic Electronics, Vol. I, NAVPERS 10087 (series), and performance will be measured by a written multiple-choice examination.
- 4.0 ANALYZE the internal structure and operation of vacuum tube circuits by identifying elements and their function in SOLVING problems in terms of voltage, current, resistance, and biasing. Responses must be in accordance with information outlined in Basic Electronics, Vol. I, NAVPERS 10087 (series). Performance will be measured by a written multiple-choice examination. A formula sheet will be provided.

ENABLING OBJECTIVES

- 1.1 SOLVE problems involving addition, subtraction, multiplication, and division of radicals and exponents, using the laws of exponents. Response must be in accordance with Mathematics, Vol. I, NAVPERS 10069 (series). Performance will be measured by a written multiple-choice examination.
- 1.2 SOLVE problems involving the addition, subtraction, multiplication, division, evaluation, and simplification of algebraic expressions. Response must be in accordance with Mathematics, Vol. I, NAVPERS 10069 (series).

SOLVE for total capacitance, RC time, current, and voltage values of a simple RC switching circuit. Response must be in accordance with Basic Electricity, NAVPERS 10086 (series). Performance will be measured by a written multiple-choice examination. A formula sheet and a Universal Time Constant Chart will be provided.

SOLVE for total inductance, L/R time, current, and voltage values of a simple L/R switching circuit. Response must be in accordance with Basic Electricity, NAVPERS 10086 (series). Performance will be measured by a written multiple-choice examination. A formula sheet and a Universal Time Constant Chart will be provided.

SOLVE for unknown current, voltage, and resistance values in electronic circuits containing source characteristics and voltage dividers. Response must be in accordance with Basic Electricity, NAVPERS 10086 (series). Performance will be measured by a written multiple-choice examination. A formula sheet will be provided.

SOLVE for unknown values of current, voltage, reactance, and power in series and parallel a-c circuits. Response must be in accordance with Basic Electricity, NAVPERS 10086 (series). Performance will be measured by a written multiple-choice examination. A formula sheet and trigonometric tables will be provided.

SOLVE for unknown values of current, voltage, reactance, frequency, bandwidth, and circuit "Q", in series and parallel resonant circuits. Response will be in accordance with Basic Electronics, Vol. I, NAVPERS 10087 (series). Performance will be measured by a written multiple-choice examination. A formula sheet and trigonometric tables will be provided.

SELECT, from a given list, correct statements concerning the structure of an atom, given an element from the Periodic Table of Chemical Elements. Responses must be in accordance with Basic Electronics, Vol. I, NAVPERS 10087 (series). Performance will be measured by a written multiple-choice examination.

SELECT, from given lists, correct statements related to the properties of heat, sound, cryogenics, and the electron.

ETERMINE normal biasing polarities of semiconductor junctions by ANALYZING majority and minority current through a given semiconductor circuit. Responses must be in accordance with quantum principles outlined in Basic Electronics, Vol. I, NAVPERS 10087 (series). Performance will be measured by a written multiple-choice examination.

ETERMINE biasing arrangements of semiconductor circuits by SOLVING problems in terms of voltage, current, reactance, and frequency. Responses must be in accordance with Basic Electronics, Vol. I, NAVPERS 10087 (series). Performance will be measured by a written multiple-choice examination. A formula sheet will be provided.

ETERMINE capabilities, electrical characteristics, advantages and disadvantages of given semiconductor circuits by SOLVING problems in terms of voltage, current, reactance, and frequency. Responses must be in accordance with Basic Electronics, Vol. I, NAVPERS 10087 (series). A formula sheet will be provided.

MPUTE decimal gain and loss in terms of the voltage and current of a given semiconductor amplifier circuit. Responses must be in accordance with Basic Electronics, Vol. I, NAVPERS 10087 (series). A formula sheet will be provided. Performance will be measured by a multiple-choice examination.

BUILD basic semiconductor amplifier circuits (under supervision). MEASURE values and RECORD measurements, calculate and evaluations on a job sheet, given necessary test equipment and an RCA 6F16 transistor trainer. Accuracy will be measured in accordance with information contained in Basic Electronics, Vol. I, NAVPERS 10087 (series).

ELECT, from given lists, the names and functions of the elements contained within a vacuum-tube. Responses must be in accordance with information outlined in Basic Electronics, Vol. I, NAVPERS 10087 (series). Performance will be measured by a written multiple-choice examination.

OLVE problems in terms of voltage, current, resistance, and biasing, using vacuum-tube formulas and tube constants. Responses must be in accordance with information outlined in Basic Electronics, Vol. I, NAVPERS 10087 (series).

Y Notice.	
o Use the Student's Guide	
II Class Schedule	
II Homework Schedule.	
Learning Objectives	

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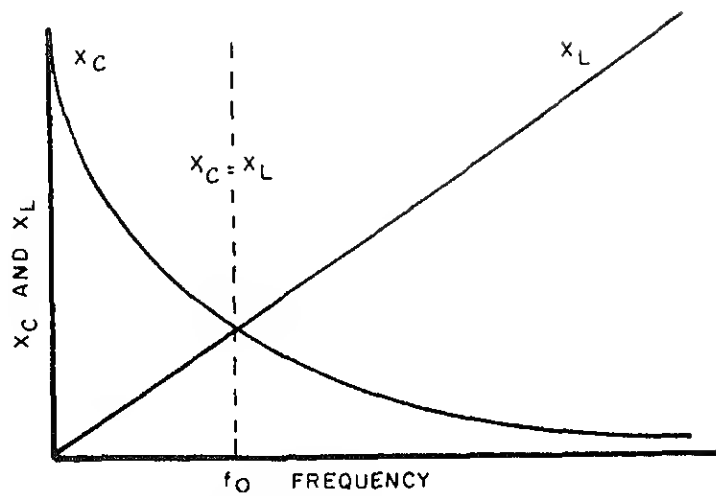
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ination Sheet 2.4.2I	
aking Sheet 2.4.1N.	
Sheet 2.5.1D.	
ination Sheet 2.6.1I	
aking Sheet 2.6.1N.	
Sheet 2.7.1D.	
ination Sheet 2.8.1I	
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Sheet 2.9.1D.	
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aking Sheet 2.11.1N	

Information Sheet 2.13.1I.
Notetaking Sheet 2.13.1N
Information Sheet 2.14.1I.
Notetaking Sheet 2.14.1N
Notetaking Sheet 2.15.1N
Notetaking Sheet 2.16.1N
Notetaking Sheet 2.17.1N
Formula Sheet	

OUTLINE:

General Information

Resonant Frequency



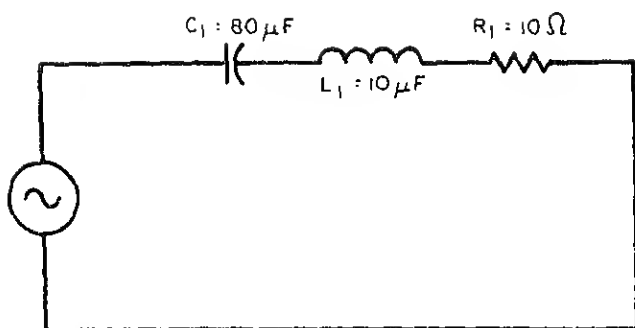


Figure 2. Series Resonant Circuit

III. Resonant Series Circuit Analysis

RLC Circuit Analysis

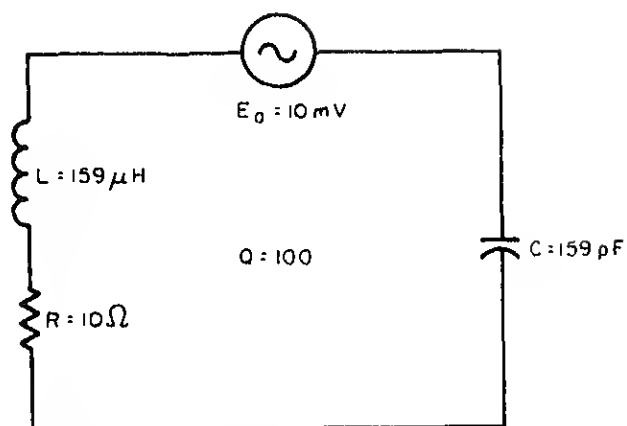
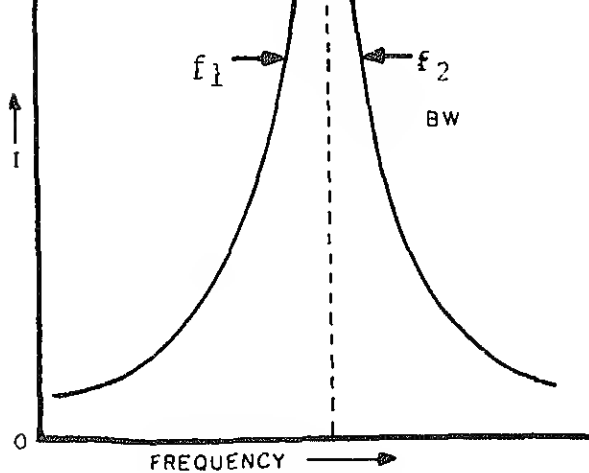
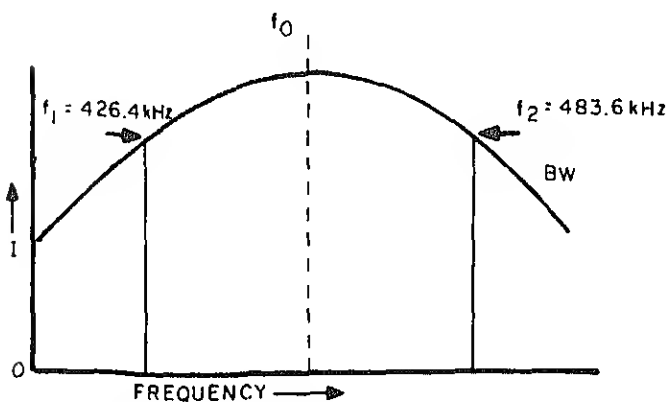


Figure 3. Series RLC circuit



(A) HIGH Q CURRENT CURVE



(B) LOW Q CURRENT DRIVE

Figure 4. Bandwidth curves

. Shrader, Electronic Communication, Fourth Edition,
Mill, Inc., 1980, Chapter 8, pages 123-131.

OUTLINE:

1 Parallel Resonance

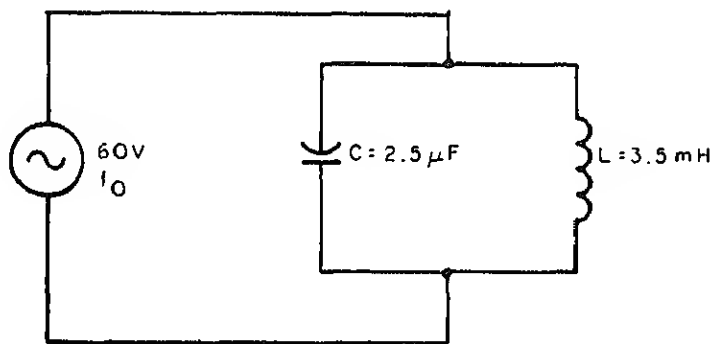


Figure 1. Parallel LC Circuit at Resonance

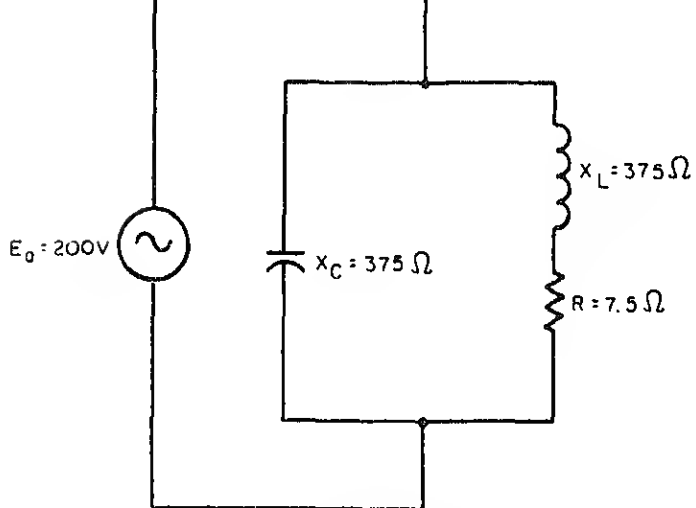
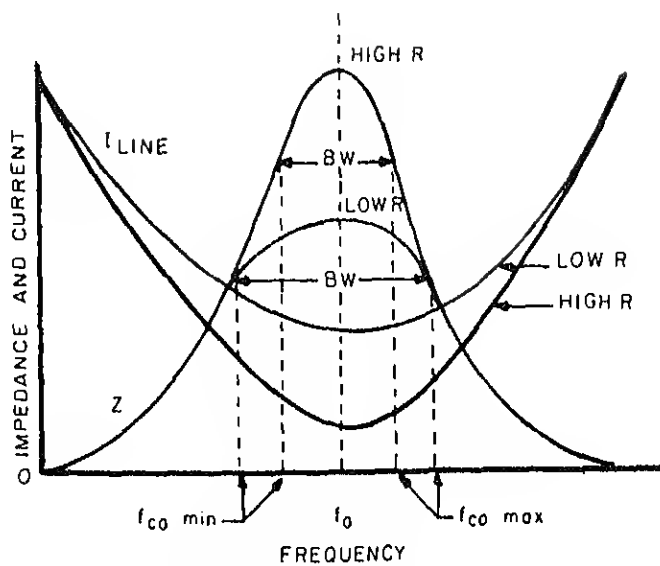


Figure 2. Parallel Resonant Circuit with Parallel Resistance.

III. Bandwidth Considerations



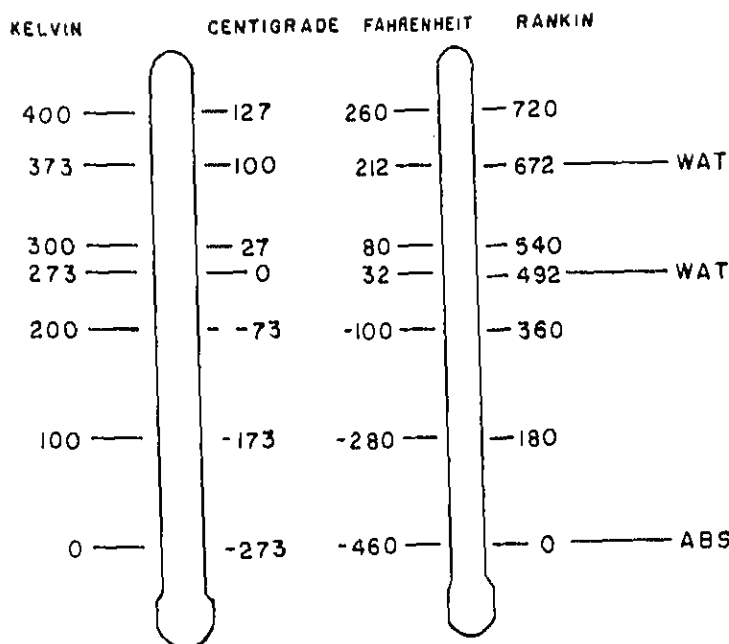
Metcalf, Trinklein, and Lefler. Modern Physics.
Holt, Rinehart, and Winston, 1968. Chapters 1, 7,
27.

OUTLINE

tter

III. The Relationship Between Matter and Energy

IV. Cryogenics



ELEMENT	TEMPERATURE AT WHICH ELEMENT BECOMES SUPERCONDUCTIVE
niobium	8.0 K.
lead	7.2 K.
antimony	4.4 K.
mercury	4.2
thorium	1.4
aluminum	1.2
zinc	0.91
titanium	0.4

Figure 2. Superconductivity Chart

<u>VELOCITY OF SOUND</u>	<u>MEDIUM</u>
1,087 FT./SEC	IN AIR AT 32° F
4,794 FT./SEC	IN WATER
16,500 FT./SEC	IN STEEL

Figure 3. Velocity of Sound in Various Mediums

VI. Light

VII. Heat

Units of heat measurement

Methods of heat transference

standing of basic physical and chemical properties is to the study of electronics. Even the more complex devices can be reduced to a study of electron behavior or gases. To follow explanations for semiconductor for example, the technician must have a knowledge of together to make a crystal.

: Dull, Metcalf, and Williams. Modern Physics. New York, N.Y.: Holt, Rinehart, and Winston, Inc., 1951. Chapter 6, pages 133-151.

ION

INTRODUCTION TO THE PERIODIC CHART OF THE ATOMS

Many of the early scientists saw that the periodicity or rhythm to atomic behavior could be shown graphically. Today, the physical significance of such a rhythm is clear. The "Periodic Chart of the Atoms" is the graphic portrait of this significance. As late as 1870, there were only 63 elements known. At this time, some system of cataloging the atoms was attempted. First, they cataloged by atomic weights. The weights of the elements were soon found to be variable, depending on the number of isotopes. A little later, it was found that the atomic number (number of protons in the nucleus) was more stable. Even though the number of elements known did not complete the chart, it gave rise to speculation that the missing atomic numbers may be unknown elements. By 1900, the inert gases were discovered and the chart began to fill out. In 1913, isotopes were discovered. They also fit into the rhythm of the chart. An isotope is a basic element with a different atomic weight. It was simply a matter of listing all isotopes of an element under the same position on the Periodic Chart; they all have the same atomic number but different atomic weights. Today, we have the Periodic Chart in its entirety from Atomic Number 1 to Atomic Number 103. Refer to figure 1, Periodic Chart; there are no elements between the known first and last elements, but this does not mean to say that there are no more beyond 103. Even the men who built our modern chart left space for the

of outermost planets of various sizes. The Periodic System is complete with all stable atoms discovered and their atomic numbers and position. The outer planet system is completed by the discovery of the six inert gas atoms, Group VIII atoms. Each row (or doublet) ends with one of these inert atoms.

II. PERIODIC CHART DATA

A. Atomic symbol

1. All atoms have symbols. The "Periodic Chart" shows the atomic symbols; examples are hydrogen, H; oxygen, O; and uranium, U.
2. All elements exist in one of three physical forms: solids, liquids, or gases. The color of each element's symbol by a color that represents the form in which it is found to exist in nature (not shown in figure 1).
3. Black symbols represent solids. Some examples of solids are carbon, silicon, iron, and gold.
4. Blue symbols represent liquids. There are only two known liquids; bromine, mercury, gallium, and cesium.
5. Orange symbols represent gases. Some examples of gases are hydrogen, oxygen, argon, krypton, and xenon.

B. Atomic number

1. The atomic number appears on the chart as a black number. Refer to figure 1, "Periodic Chart of the Elements".
2. The atomic number represents the number of protons in the nucleus of the atom. Since atoms are electrically neutral, they must contain equal numbers of protons and electrons. Thus, the atomic number also represents the number of electrons in an atom. The atomic number is the "key" to the periodic chart. Refer to "Distribution of Electrons"; starting with hydrogen, which has one proton and one electron, each element increases by one proton and one electron in the next element.

^{26}Fe --Iron, $Z = 26$

^{54}Xe --Xenon, $Z = 54$

If a proton is added to the nucleus and an electron is added to the shells, a new atom is formed. If a neutron enters the nucleus a new atom is not formed. Although dead weight is added, such an atom behaves chemically as before. These atoms with the same number of protons but different numbers of neutrons are called isotopes of the same element.

Example of an element with three isotopes is hydrogen (H). Shown in figure 2 are the three isotopes of hydrogen.

The basic hydrogen atom, protium, has one proton and no neutrons.

GROUPS →

	I	II	III	IV	V	VI	VII	VIII	IX	X
1	H Hydrogen 1.008							2 He Helium 4.0026		
2	3 Li Lithium 6.94	4 Be Beryllium 9.012	5 B Boron 10.81	6 C Carbon 12.011	7 N Nitrogen 14.006	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.179		
3	11 Na Sodium 22.99	12 Mg Magnesium 24.305	13 Al Aluminum 26.98	14 Si Silicon 28.086	15 P Phosphorus 30.973	16 S Sulfur 32.06	17 Cl Chlorine 35.453	18 Ar Argon 39.948		
4	19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.69
	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.8		
5	37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.905	46 Pd Palladium 106.36
	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.757	52 Te Tellurium 127.6	53 I Iodine 126.905	54 Xe Xenon 131.30		
6	55 Cs Cesium 132.905	56 Ba Barium 137.327	57 La Lanthanum 138.905	58 Ce Cerium 140.12	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 145	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25
	67 Tb Terbium 158.925	68 Dy Dysprosium 162.50	69 Ho Holmium 164.930	70 Er Erbium 167.259	71 Tm Thulium 168.934	72 Yb Ytterbium 173.054	73 Lu Lutetium 174.967	74 Hf Hafnium 178.49	75 Ta Tantalum 180.948	76 W Tungsten 183.84
	77 Ir Iridium 186.227	78 Pt Platinum 195.084	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium 209	85 At Astatine 210	86 Rn Radon 222
7	87 Fr Francium 223	88 Ra Radium 226	89 Ac Actinium 227	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244	95 Am Americium 243	96 Cm Curium 247
8	97 Bk Berkelium 247	98 Cf Californium 251	99 Es Einsteinium 252	100 Fm Fermium 257	101 Md Mendelevium 258	102 No Nobelium 259	103 Lr Lawrencium 262	104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 266
9	107 Bohrium 264	108 Hassium 277	109 Meitnerium 268	110 Darmstadtium 271	111 Roentgenium 272	112 Copernicium 285	113 Nihonium 284	114 Flerovium 289	115 Moscovium 288	116 Livermorium 293
10	117 Tennessine 289	118 Oganesson 294								

Figure 1

ELEMENT	SHELLS					ATOMIC NO.	ELEMENT	SHELLS					P
	K	L	M	N	O			K	L	M	N	O	
Hydrogen	1					43	Technitium	2	8	18	13	2	
Helium	2					44	Ruthenium	2	8	18	14	2	
Lithium	2	1				45	Rhodium	2	8	18	15	2	
Beryllium	2	2				46	Palladium	2	8	18	16	2	
Boron	2	3				47	Silver	2	8	18	18	1	
Carbon	2	4				48	Cadmium	2	8	18	18	2	
Nitrogen	2	5				49	Indium	2	8	18	18	3	
Oxygen	2	6				50	Tin	2	8	18	18	4	
Fluorine	2	7				51	Antimony	2	8	18	18	5	
Neon	2	8				52	Tellurium	2	8	18	18	6	
Sodium	2	8	1			53	Iodine	2	8	18	18	7	
Magnesium	2	8	2			54	Xenon	2	8	18	18	8	
Aluminum	2	8	3			55	Cesium	2	8	18	18	8	1
Silicon	2	8	4			56	Barium	2	8	18	18	8	2
Phosphorus	2	8	5			57	Lanthanum	2	8	18	18	9	2
Sulphur	2	8	6			58	Cerium	2	8	18	19	9	2
Chlorine	2	8	7			59	Praseodymium	2	8	18	20	9	2
Argon	2	8	8			60	Neodymium	2	8	18	21	9	2
Potassium	2	8	8	1		61	Promethium	2	8	18	22	9	2
Calcium	2	8	8	2		62	Samarium	2	8	18	23	9	2
Scandium	2	8	9	2		63	Europium	2	8	18	24	9	2
Titanium	2	8	10	2		64	Gadolinium	2	8	18	25	9	2
Vanadium	2	8	11	2		65	Terbium	2	8	18	26	9	2
Chromium	2	8	12	2		66	Dysprosium	2	8	18	27	9	2
Manganese	2	8	13	2		67	Holmium	2	8	18	28	9	2
Iron	2	8	14	2		68	Erbium	2	8	18	29	9	2
Cobalt	2	8	15	2		69	Thulium	2	8	18	30	9	2
Nickel	2	8	16	2		70	Ytterbium	2	8	18	31	9	2
Copper	2	8	18	1		71	Lutetium	2	8	18	32	9	2
Zinc	2	8	18	2		72	Hafnium	2	8	18	32	10	2
Gallium	2	8	18	3		73	Tantalum	2	8	18	32	11	2
Germanium	2	8	18	4		74	Tungsten	2	8	18	32	12	2
Arsenic	2	8	18	5		75	Rhenium	2	8	18	32	13	2
Selenium	2	8	18	6		76	Osmium	2	8	18	32	14	2
Bromine	2	8	18	7		77	Iridium	2	8	18	32	15	2
Krypton	2	8	18	8		78	Platinum	2	8	18	32	16	2
Rubidium	2	8	18	8	1	79	Gold	2	8	18	32	18	1
Strontium	2	8	18	8	2	80	Mercury	2	8	18	32	18	2
Yttrium	2	8	18	9	2	81	Thallium	2	8	18	32	18	3
Zirconium	2	8	18	10	2	82	Lead	2	8	18	32	18	4
Niobium	2	8	18	11	2	83	Bismuth	2	8	18	32	18	5
Molybdenum	2	8	18	12	2	84	Polonium	2	8	18	32	18	6

43	Technitium	2	8	18	13	2	
44	Ruthenium	2	8	18	14	2	
45	Rhodium	2	8	18	15	2	
46	Palladium	2	8	18	16	2	
47	Silver	2	8	18	18	1	
48	Cadmium	2	8	18	18	2	
49	Indium	2	8	18	18	3	
50	Tin	2	8	18	18	4	
51	Antimony	2	8	18	18	5	
52	Tellurium	2	8	18	18	6	
53	Iodine	2	8	18	18	7	
54	Xenon	2	8	18	18	8	
55	Cesium	2	8	18	18	8	1
56	Barium	2	8	18	18	8	2
57	Lanthanum	2	8	18	18	9	2
58	Cerium	2	8	18	19	9	2
59	Pras'mium	2	8	18	20	9	2
60	Neodmium	2	8	18	21	9	2
61	Promethium	2	8	18	22	9	2
62	Samarium	2	8	18	23	9	2
63	Europium	2	8	18	24	9	2
64	Gadolinium	2	8	18	25	9	2
65	Terbium	2	8	18	26	9	2
66	Dysprosium	2	8	18	27	9	2
67	Holmium	2	8	18	28	9	2
68	Erbium	2	8	18	29	9	2
69	Thulium	2	8	18	30	9	2
70	Ytterbium	2	8	18	31	9	2
71	Lutetium	2	8	18	32	9	2
72	Hafnium	2	8	18	32	10	2
73	Tantalum	2	8	18	32	11	2
74	Tungsten	2	8	18	32	12	2
75	Rhenium	2	8	18	32	13	2
76	Osmium	2	8	18	32	14	2
77	Iridium	2	8	18	32	15	2
78	Platinum	2	8	18	32	16	2
79	Gold	2	8	18	32	18	1
80	Mercury	2	8	18	32	18	2
81	Thallium	2	8	18	32	18	3
82	Lead	2	8	18	32	18	4
83	Bismath	2	8	18	32	18	5
84	Polonium	2	8	18	32	18	6

85	Astatine	2	8	18	32	18	7
86	Radon	2	8	18	32	18	8
87	Francium	2	8	18	32	18	8
88	Radium	2	8	18	32	18	8
89	Actinium	2	8	18	32	18	9
90	Thorium	2	8	18	32	19	9
91	Protactinium	2	8	18	32	20	9
92	Uranium	2	8	18	32	21	9
93	Neptunium	2	8	18	32	22	9
94	Plutonium	2	8	18	32	23	9
95	Americium	2	8	18	32	24	9
96	Curium	2	8	18	32	25	9
97	Berkelium	2	8	18	32	26	9
98	Californium	2	8	18	32	27	9
99	Einsteinium	2	8	18	32	28	9
100	Fermium	2	8	18	32	29	9
101	Mendelevium	2	8	18	32	30	9
102	Nobelium	2	8	18	32	31	9
103	Lawrencium	(Unknown)					

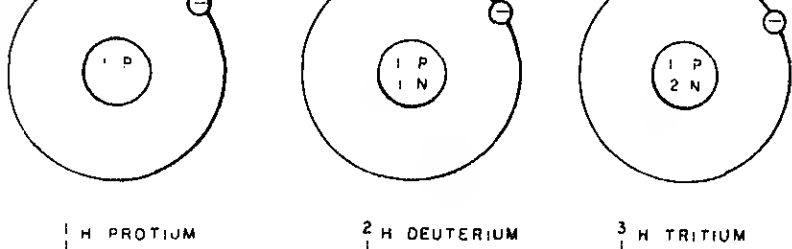


Figure 2

The second hydrogen atom, deuterium, has 1 proton and 1 neutron. The third hydrogen atom, tritium, has 1 proton and 2 neutrons. The three hydrogen isotopes (${}^1_1\text{H}$, ${}^2_1\text{H}$, and ${}^3_1\text{H}$) given individual names to identify them. These names are protium (${}^1_1\text{H}$), deuterium (${}^2_1\text{H}$), and tritium (${}^3_1\text{H}$). Almost all elements have more than one isotope.

Atomic Weight

Atomic weight is the weighted average of the isotopes based on their relative abundance. The atomic weight is shown in figure 1, "Periodic Chart."

The average weight of the three isotopes in hydrogen is 1.00797 AMU (Atomic Mass Units) ($1 \text{ AMU} = 1.66 \times 10^{-24} \text{ grams}$). The figure for atomic weight is a relative number and its only real importance is to the chemist.

The atomic weight is not the same as the number of protons and neutrons in the nucleus. The mass number is the number of protons and neutrons and is a whole number.

Electron Shells

The orbits in which electrons must revolve about the nucleus of an atom are called electron shells, or quantum levels. The shells are labelled K, L, M, N, O, P, Q, from the innermost (K) to the outermost (Q). Table I,

shell fills first, then the "L" shell, and so on. This is not an absolute law; there are some irregularities. At this time we are not interested in the irregularities.

3. Study Table 1, "Distribution of Electrons" that none of the elements has more than two electrons in the first shell (K). In the case of hydrogen, only one electron and it is in the "K" shell. In the case of other elements, only two electrons can exist in the "K" shell. To predict the maximum number of electrons that may occupy any given shell, use the equation $2N^2$ (where N indicates the number of the shells). In the case of the first shell (K), the equation states:

$$2(N^2)$$

$$2(1^2)$$

$$2(1) = 2 \text{ electrons.}$$

The "K" shell in any element cannot contain more than two electrons. In the second shell (L), the equation states:

$$2(N^2)$$

$$2(2^2)$$

$$2(4) = 8 \text{ electrons.}$$

The "L" shell in any element cannot contain more than eight electrons. All elements do contain the maximum number of electrons except those that do not have enough electrons available to fill the shell ($Z = 1$ to $Z = 9$). For example, Germanium; the equation states: "K" shell, 2 electrons; "L" shell, 8 electrons; "M" shell, 18 electrons; and "N" shell, 32 electrons. Refer to Table 1, "Distribution of Electrons." The table shows that germanium has 32 electrons (Atomic Number 32). The 32 electrons are distributed "K" = 2, "L" = 8, "M" = 18, and "N" = 4. The last shell in germanium (N) only contains four electrons, even though the equation states that it can contain 32.

partially filled? An example of this is potassium, (19): notice the "K" shell = 2, "L" shell = 8, "M" = 8, "N" shell = 1. To explain why the "M" shell takes the one electron that went to the "N", we must delve deeper into the construction of the shells.

S, L, M, N, O, P, Q shells are called the main shells. Each main shell after the "K" shell is made of subshells. The number of subshells (or subshells) that are present within a main shell is in figure 3.

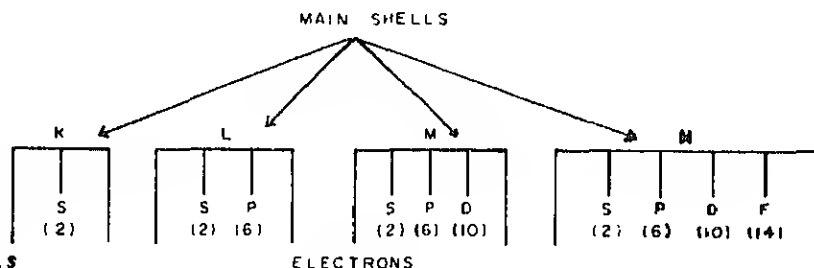


Figure 3

in figure 3, each subshell that exists within a shell as a set number of electrons. Each one of the "S" subshells in any main shell contains two electrons. Each succeeding subshell always has four electrons more than its preceding subshell. Remember, as stated earlier that a main shell will fill, in some cases, before the next main shell begins. To be specific, a subshell will fill prior to the next main shell out within a main shell. If a subshell in the current main shell cannot be filled, the electrons will move out to the "S" subshell in the "N" main shell. An example of this is again potassium ($Z = 19$). Refer to figure

Figure 4

3. In the case of potassium, the "M" shell has shell full. The last electron would not have the "D" subshell, so it was moved out to the "N" shell. In most cases, this will happen; this is not the law. A brief review of Table I, "Distribution of Electrons", will show that a number of elements follow from the above. The majority do have some electrons at least through the "M" shell.

G. Group (or column)

1. Each group or column on the "Periodic Chart" contains atoms of similar behavior in vertical arrangement, since the Roman numeral number is equivalent, in general, to the number of valence electrons. The properties of the atoms. The Roman numeral at the head of each column indicates the column number. In general the number of such outer electrons.
2. The grouping of the elements according to valence electrons gives a ready reference to the characteristics of the particular elements. Elements in Group I all have a valence of one electron. At the top of the "Periodic Chart", figure 1, that copper is in Group I; copper is a good conductor. On the right end of the chart is Group VIII. Group VIII contains all the inert elements. Inert elements are elements whose outermost shell (or subshell) is full. These elements in Group VI readily combine chemically with other elements. Elements in Group VII will not give up or take on electrons; thus they are stable or inert - good electrical insulators.
3. Groups I, II, and III are electrical conductors. Elements in Group I will readily give up an electron. These elements in Group II give up an electron in an attempt to gain a stable configuration and become chemically stable.

shell within a shell). The breakdown of the elements can be seen by referring to Table 1, "Distribution of Electrons." Note that the "inert" elements are underlined.

Group IV is the "semiconductor" group. These elements have four electrons in their valence. They will either lose or gain electrons in an attempt to become electronically stable. For this reason, Group IV elements are between conductors and insulators - semiconductors.

the last twenty years, literature on solid state research. The information accumulated regarding the copper, nickel and germanium and silicon crystals led to the invention of the transistor. A semiconductor, from which transistors are made, is an electronic conductor with resistivity intermediate between that of a conductor and an insulator. The phenomenon of transistor action is unexplainable by electron theory; a new theory is used which is called hole flow. It is essential that the technician have a basic understanding of solid state physics in order to be able to understand the operation of

S. Kiver, Transistor and Integrated Electronics. New York: McGraw-Hill Book Company, 1972, Fourth Edition.

W. R. Sturgis and Osterheld, Essentials of Radio--Electronics. New York: McGraw-Hill Book Company, 1961, Second Edition.

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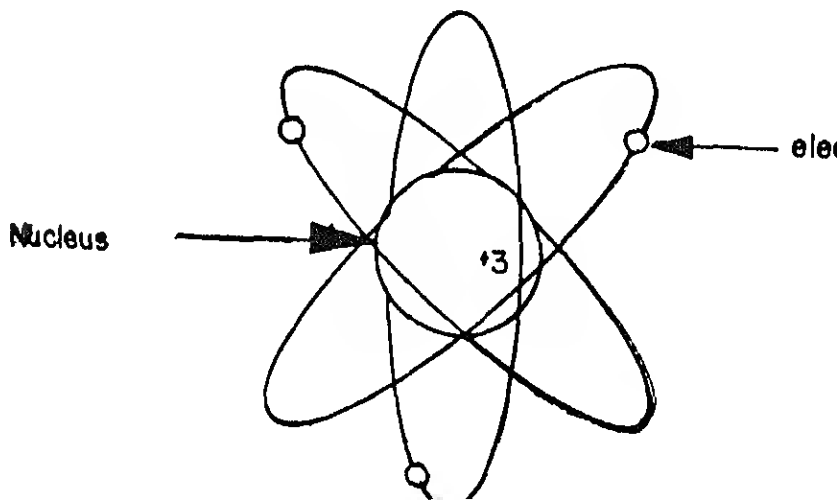
The history of the transistor is, in large measure, the story of how matter and how the scientists at the Bell Telephone Laboratories have been able to make that matter amplify electric currents. If we consider the vacuum tube as man's most significant advance into the field of communication, then the transistor must certainly be heralded as man's second most important step.

The first public announcement of the transistor was made in 1948. Thus, in terms of time, the transistor does not compare with vacuum tubes. In terms of application, however, it must be classed with the vacuum tube. And while there is probably no prospect that it will completely re-

- D. Operation of vacuum tubes depends upon the flow of electrons from cathode to plate and the control of intermediate grids. Operation of the transistor depends upon electron and hole flow. These two devices perform the same functions, but there are considerable differences between the two. In order to appreciate these differences, a study of atomic structure, intrinsic materials, and electrical properties of semiconductors is required.

II. Review of atomic structure

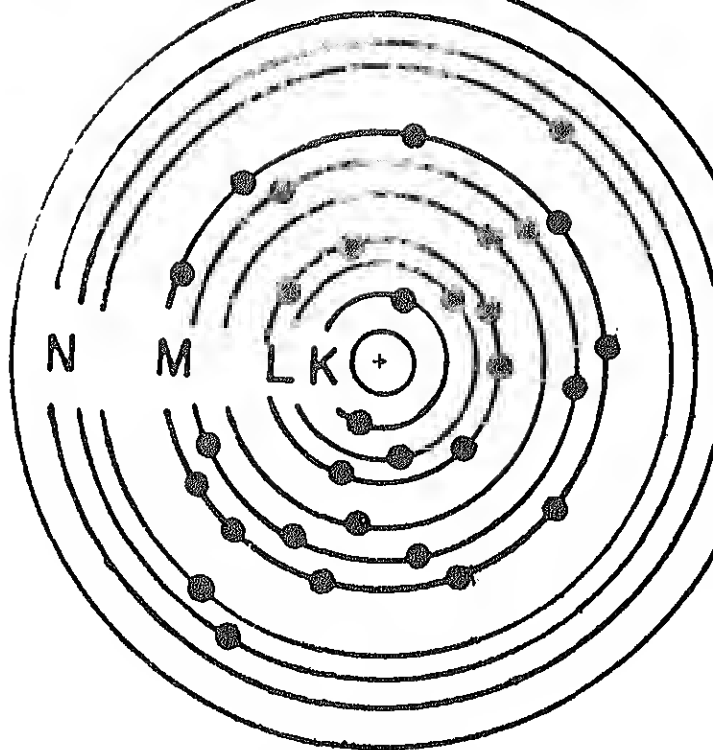
- A. Any atom may be considered to be composed of a central nucleus surrounded by electrons, which occupy various orbits (see figure 1). The nucleus contains protons and neutrons, which have no electric charge, and protons are positively charged. Neutrons and protons have approximately the same weight, and the combined weight of neutrons and protons is referred to as the relative atomic weight of the element. The number of protons in the nucleus determines the atomic number of an element. A net positive charge on the nucleus. If an atom has the usual atomic number, but a different atomic weight, it is called an isotope. It contains an abnormal number of neutrons, it is called an isotope.



the higher energy level to one which is closer to the nucleus. Conversely, an electron excited from an inner to an outer orbit will absorb energy. If by some means (electric fields, high temperatures, radiation, etc.) the total energy of an electron is increased, the electron will be torn from the parent atom. Under these conditions, ionization or breakdown has occurred.

Electrons have been found to surround the nucleus in shells as shown in figure 2 and the manner in which they are distributed is:

<u>Main Shell</u>		<u>Sub Shell</u>	
K	2 electrons	2	electrons
		s	p
L	8 electrons	2	6 electrons
		s	p d
M	18 electrons	2	6 10 electrons
		s	p d f
N	32 electrons	2	6 10 14 electrons

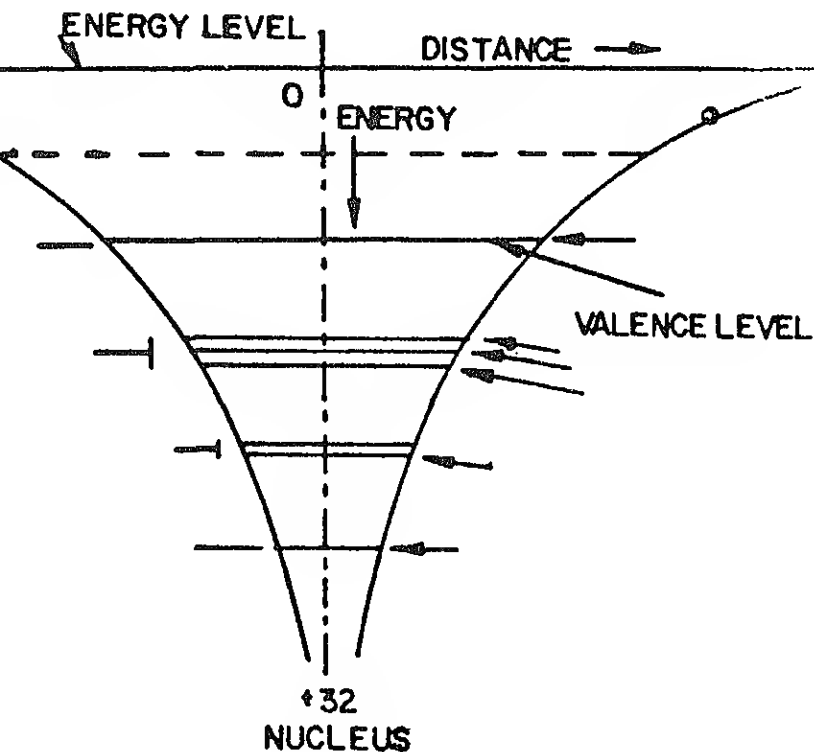


A two dimensional representation of the manner in which electrons are distributed about the nucleus of a germanium atom.

Figure 2.

- E. Electrical and chemical activity of a material is restricted to the electrons in the outer shell. The outer shell of an atom is called the valence shell. The electrons occupying orbits in these shells are called valence electrons. Unfilled orbits lying above the valence shell are called excitation levels. Imparting sufficient energy to an electron may cause it to jump into an excitation level. The applied electric field may cause a displacement process toward the region of lower positive potential. Actually, at temperature above absolute zero, there will be some probability of finding an electron in the excitation level because of thermal agitation. As we shall see later, this is one of the most important factors in the electrical activity of a material.

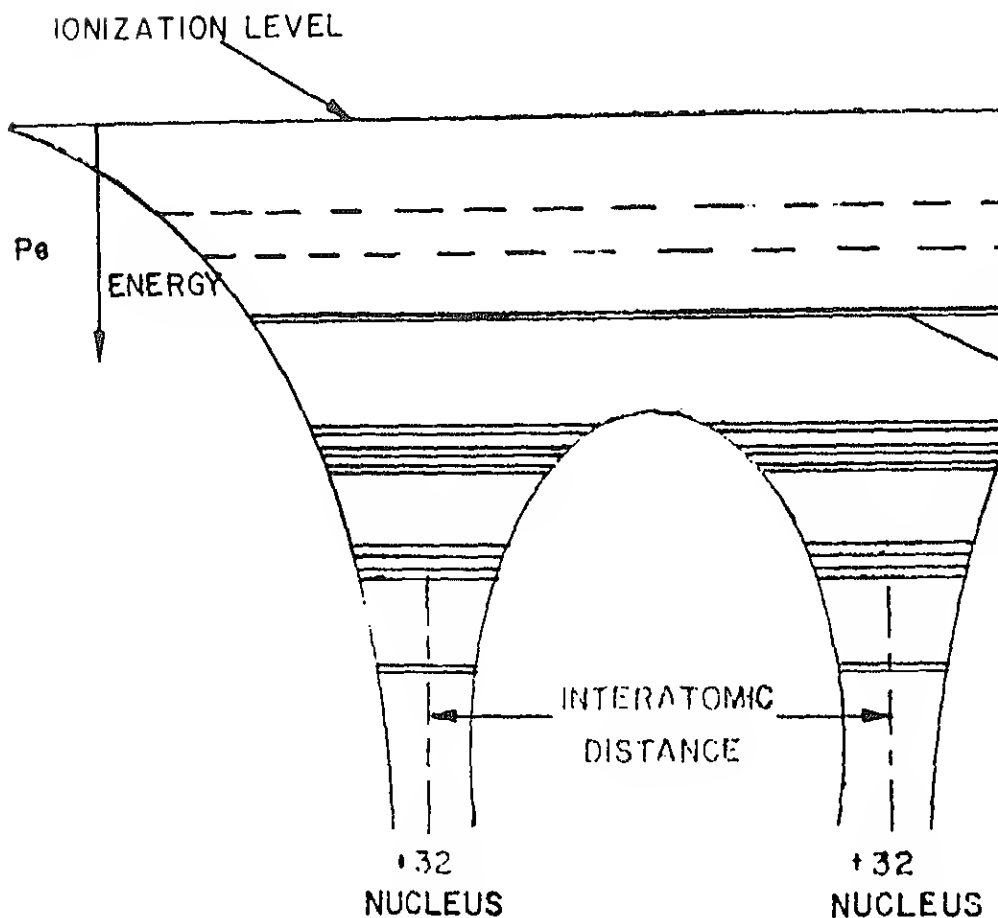
electrons. Silicon has an atomic number of 14, means there are 2 electrons in the K shell, 8 in the M in the M shell; therefore, silicon has 4 valence ns. A plot of the total energy of an electron as distance from the germanium nucleus increases, is shown in Figure 3.



ution of energy levels for a germanium atom.

Figure 3.

an electron in one atom has a counterpart in the other atom has a slightly different energy level, and they can switch levels continuously. Note in figure 4 that the valence and excitation levels are common to both atoms. This means a valence electron could travel to another and vice versa without requiring any external energy.

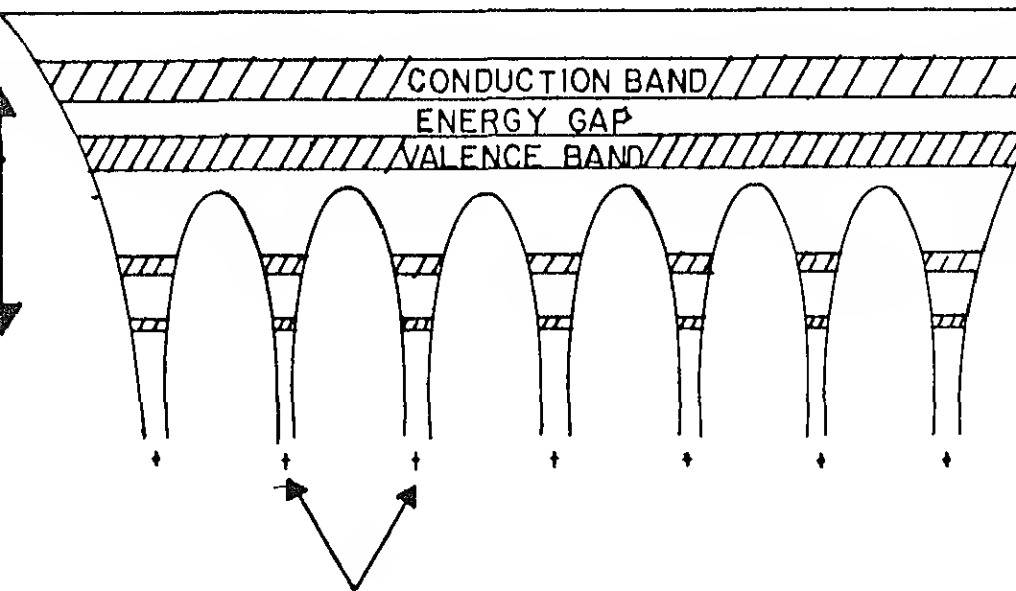


When two similar atoms are brought together, an interaction occurs which permits additional levels.

Figure 4.

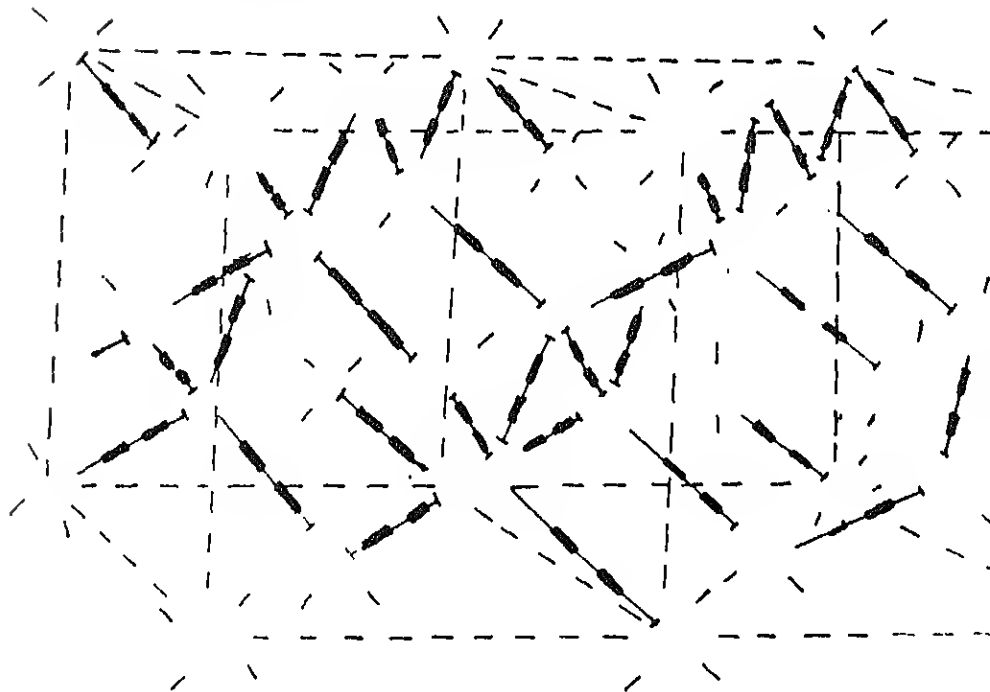
The various valence levels form the valence band. The first excitation levels are lumped into the conduction band. For conduction to occur when an electric field applied to the crystal of figure 5, electrons must be accelerated in order to change their total energy. Because of their discrete behavior their total energy increase only if they can be excited into a new level in a crystal, the valence band is completely filled, conduction can occur only when sufficient stimuli is imparted to raise some electrons from the valence band to the conduction band. Here there are many levels through which an electron may be accelerated. Note that accelerating an electron from the valence band into the conduction band leaves a vacant level in the valence band. This means electrons can now accelerate in the valence band. The vacant level left in the valence band is a hole.

ON LEVEL



adjacent atoms to form pairs of shared electron sharing is called covalent bonding covalent bonds bind the germanium atoms into orderly, geometric pattern within the crystal

2. Figure 6 is a simplified illustration of the arrangement of a crystal structure. The ion of each atom has an overall positive charge locked into the structure in an orderly manner. A positive ion is repelled by the similarly charged positive ion from various directions, thereby stabilizing the positive of the ion in the structure. The large mass of the ion also contributes to the stability.



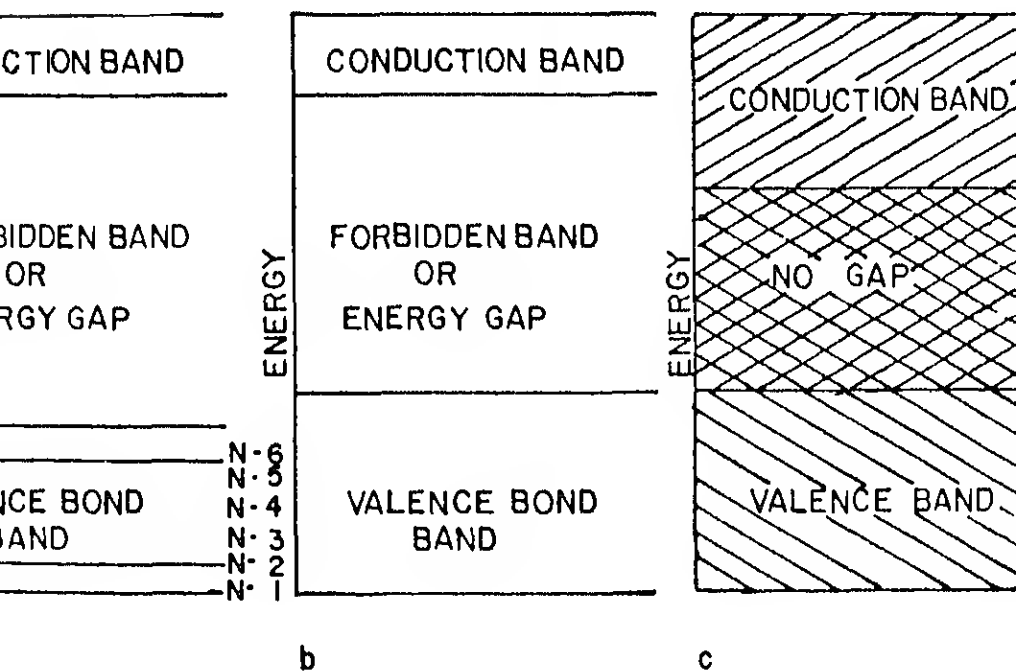
Pure germanium crystal, lattice structure.

Figure 6.

3. Materials may be broadly classified as insulators, semiconductors, or conductors according to their

Insulators

- a. An insulator may be defined as a material which offers high resistance to the flow of electrons. The basic reason for offering such a high opposition to the flow of electrons is that free electrons are relatively scarce in such materials. referring to figure 7(a), which illustrates the energy diagram of an insulator's valence and conduction band, it can be seen that the energy gap is wider than that of the semiconductor and conductor. The energy levels within the insulator's valence band are filled, and the energy levels in the conduction band are empty. This means the valence electrons have very little opportunity to undergo changes from one valence energy to another.



Energy bands: (a) insulator (b) semiconductor

motions, and virtually no mobile electrons are available for participation in the conduction process.

5. Semiconductors--Figure 7(b) is the energy level diagram for a semiconductor. The energy levels within the valence band are filled, as in the case of insulators. Valence electrons have very little opportunity to change levels in the valence band, since the lower energy vacant levels are filled. The forbidden gap between the valence and conduction band is not as great as in an insulator. The probability of valence electrons acquiring the necessary increment of thermal energy is better, since smaller packages of thermal energy are required. This energy gap, at room temperature, is about 0.7 eV for germanium and 1.2 eV for silicon. Because of the lower height of the forbidden gap, semiconductors have resistivity lower than insulators, but considerably higher than conductors. electron volt (eV) is the Kinetic energy of an electron when accelerated through a one volt potential difference.
6. Conductors - The energy diagram of a conductor is in figure 7(c). Notice the overlap between the valence levels and lower conduction levels. Electrons, in such a material, require very small increments of thermal energy to be excited into the conduction level. The probability of this occurring at room temperature is very high. Such a material displays low resistance (high conductivity). Such is the condition which exists in metals and conductors.

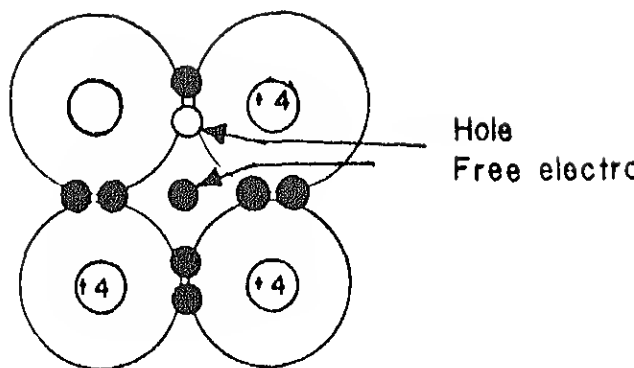
*Conductivity is the reciprocal of resistivity; or,

astically alter their electrical properties. For this reason, a semiconductor would not be called truly intrinsic unless the impurity level is very small--for germanium less than 1 part impurity in 10^8 parts of germanium; for silicon the impurity content would have to be less than 1 part in 10^{12} . In practice, however, semiconductor material with somewhat larger impurity concentrations than these is sometimes referred to as intrinsic.

At temperatures of absolute zero, intrinsic germanium or silicon can be shown as it is in figure 6. All of the valence electrons are tightly held by the parent atoms and also, through the covalent bonds by other atoms. The electrons are not free to move through the crystal structure and, thus cannot conduct electricity. For this reason, an intrinsic semiconductor at absolute zero behaves like an insulator. It is a very poor conductor of electricity.

Consider what happens as the temperature is increased. An increase in temperature means an increase in the heat energy of each atom. This increase in energy may be given to one of the atom's valence electrons. By this process, a valence electron may acquire sufficient energy to break away from its parent atom and, in so doing, break one of the covalent bonds. This electron is now free to wander through the crystal structure and is not bound to any particular atom. It is called a free electron and can now act as a current carrier if a voltage is applied to the material. A current carrier is simply any charged particle (such as an electron) which is free to move as part of an electric current if a source of voltage is applied.

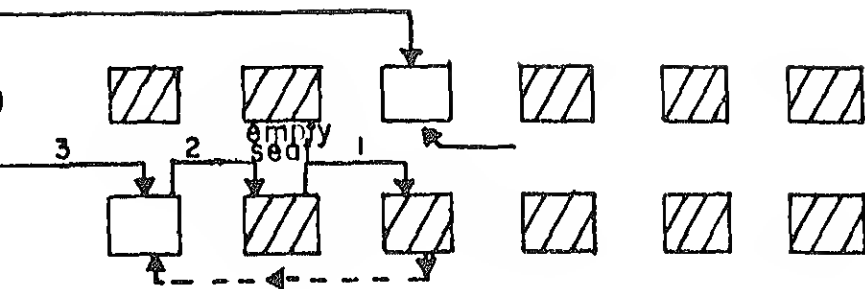
What happened back at the place where the electron left its parent atom? It left behind a vacancy or an incomplete valent bond, which is usually referred to as a hole. Figure 8 shows the crystal structure with one free electron and one hole brought about by the electron breaking away from the parent atom. This process of the formation of free electrons and holes is called thermal generation.



Creation of a free electron and a hole caused by an increase in crystal temperature.

Figure 8.

- E. The interesting thing about a hole is that it is a current carrier. If a hole is created by an electron breaking away in one atom, an electron from a neighboring atom can easily fill the hole by breaking its bond and jumping over to the first atom. When it does, it appears that the hole has moved. If you have a hole at point A and an electron at point B, when the electron fills the hole at A, it leaves a hole at B. Thus, in effect, the hole has moved from point A to point B. This can be illustrated by considering the situation when you arrive late at a train station and find the only vacant seat is in the center of the car (see figure 9).

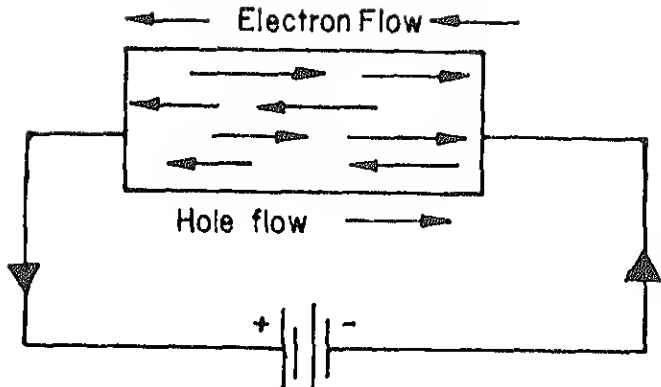


Hole movement.

Figure 9.

you can become a "free electron" and go along the row. You get to the "hole" or the people in the first two can move in sequence one seat to the right and make the move to you at the end of the row.

When a hole exists there is a net positive charge. The +4 charge of the parent atom (nucleus and inner electrons) is greater than the -3 charge of the three valence electrons. Thus, we consider the hole as having, in effect, a positive charge. When the hole moves, there is a net flow of positive charge. A voltage is applied to a semiconductor containing free electrons and holes, the free electrons will move from negative to positive, and the holes will move from positive to negative. Remembering the direction of hole movement, you can see that a hole moving to the right is really an electron moving to the left. Thus, the flow of holes from positive to negative is really the flow of negative charges (electrons) from negative to positive. You can think of current in a semiconductor as consisting of two parts; free electrons moving in one direction and holes moving in the opposite direction. To get the total current, you add the two parts. Figure 10 is a representation of the flow of charges in a semiconductor.



The flow of charges in a semiconductor due to an applied voltage.

Figure 10.

The flow of charges in a semiconductor due to an applied voltage. NOTE: There is no hole flow external to the semiconductor. Current flow in a semiconductor is by the movement of free electrons.

You may be wondering what happens to the holes when they reach the edge of the piece of semiconductor material (point B in figure 10). The answer is that some of the electrons coming from the negative battery terminal combine with the holes, filling them so that both the holes and the filling electrons disappear as charges. This process is called recombination. The rest of the electrons travel through the semiconductor as free electrons. The electrons leaving the semiconductor at B fall into one of the two categories: those which were freed at B and traveled through the crystal or those which were freed within the crystal when the holes were formed.

...current, jump from hole to hole and do not have energy to become really free. On the other hand, the free electrons have enough energy to move freely through the crystal without being tied down to any atom.

You can see from this that the free electrons are able to move faster through the crystal than the holes, which have to move in a succession of jumps. We say that the free electrons have a higher mobility than the holes.

At ordinary room temperature (approximately 25°C), the thermal energy is sufficient for a large number of free electrons and holes to exist in an intrinsic semiconductor. At room temperature intrinsic semiconductors such as germanium and silicon are fair electric conductors, being better conductors than a metal such as copper, but much poorer conductors than an insulator such as rubber. An important characteristic of an intrinsic semiconductor is that it possesses a negative temperature coefficient (resistance decreases with a rise in temperature); therefore conductivity increases with an increase in temperature. This is true because of the increased thermal agitation at higher temperatures; therefore, there are more free electrons and more holes created. In an intrinsic semiconductor with no applied voltage, the total number of free electrons equals the total number of holes.

(extrinsic) semiconductors

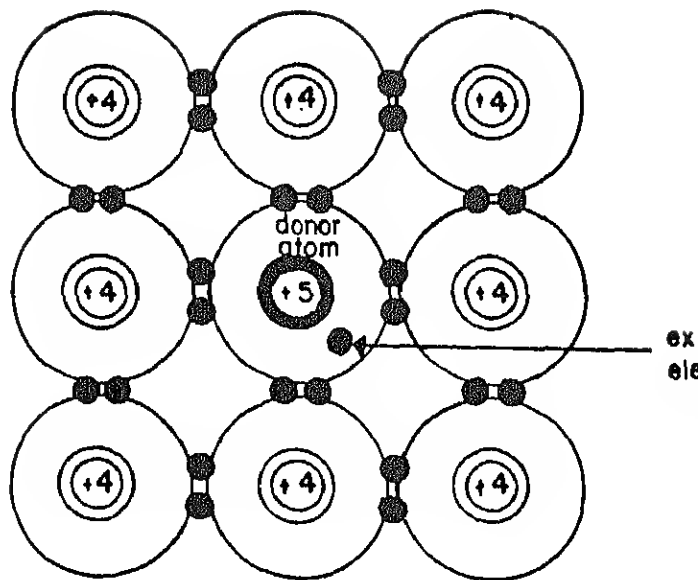
Practical semiconductors contain traces of impurities deliberately added to the material after the natural impurity level has been reduced to a negligible degree. The types of added impurities fall under two categories:

1. Elements containing five valence electrons (Pentavalent)
2. Elements containing three valence electrons (Trivalent)

The effects of each type upon the energy and electrical characteristics of germanium will be examined.

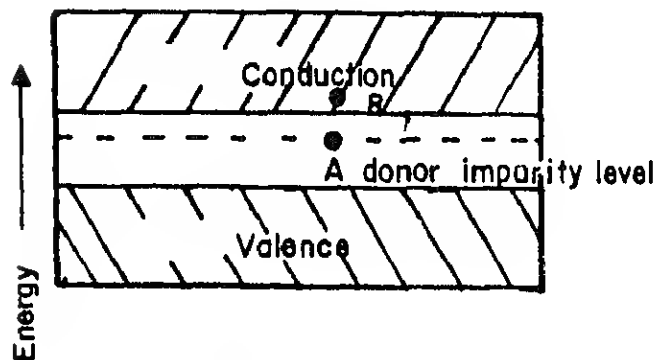
The donor or N-type crystal

1. There are a number of elements possessing five electrons in their outer shell, which are chemically comp...



The addition of an N-type impurity atom produces one free electron.

Figure 11.

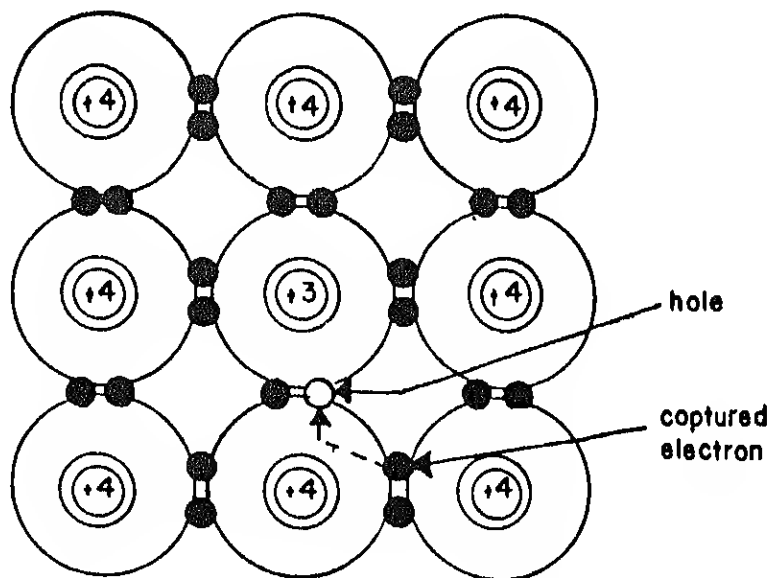


Energy distribution in donor-type germanium

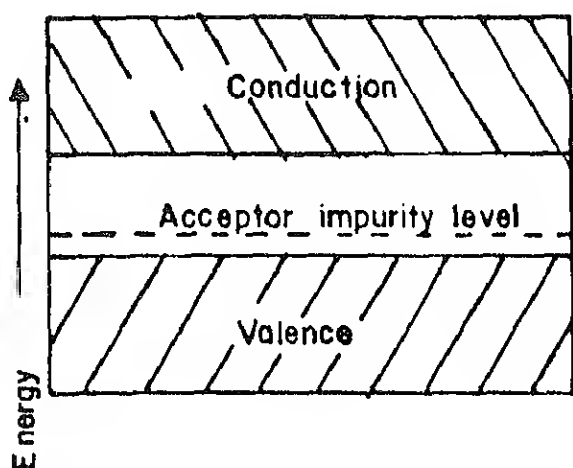
temperature is approximately 0.026 eV.

3. A crystal containing an impurity whose atoms possess five valence electrons is called a donor crystal, and it readily donates electrons to the conduction process. The conduction which occurs because of these mobile electrons, when an external electric field is applied, is called extrinsic conduction, as opposed to intrinsic conduction which is due to electrons that are elevated to the conduction region from the valence energy level. Because of the great difference in energy requirements between the two types of conduction, extrinsic conduction occurs at a much lower temperature than intrinsic conduction (where the increment of energy must be at least as high as the forbidden energy gap). At a low temperature the conductivity of the donor crystal is higher than that of a pure crystal to an extent determined by the number of impurity atoms added. The major carriers of charge in this type of material are negative, hence the term N-type crystal.

Acceptor or P-type crystal



electron from another atom to complete its arrangement, and any such three-valence element is called an "acceptor" atom. When the gallium atom has more electron than it should normally have, it becomes a negative ion. This extra electron must be at a greater distance from the gallium nucleus than the valence electrons and is therefore closer to the conduction band in terms of energy. The energy level of this electron is immediately above the valence band in figure 14.



Energy distribution in acceptor type ge

Figure 14.

- B. Notice that only a small increment of energy (0.01 eV) is required to excite a valence electron into the impurity energy level, since this level is close to the valence band rather than the conduction region. This occurs even at low temperatures, where relatively few electrons are thermally excited across the energy gap. Each valence electron excited to the impurity level leaves a vacancy (hole) in the valence band, so it is possible for valence electrons to move through the covalent band and move to another with the

directed toward the negative terminal of the external circuit. Within the extrinsic range of temperatures, at which intrinsic conduction is negligible, the significant conduction occurs by this hole current in the semiconductor. Actually, the major carriers of charge in this material are positive, hence the term P-type semiconductor.

Physical properties of semiconductor materials

Resistivity

The electric resistance of a piece of material depends on its atomic structure; on the material length; and on its cross-sectional area. Resistance can be expressed mathematically as:

$$R = \frac{PL}{A}$$

where R, L, and A are resistance, length, and cross-sectional area, respectively, and P is the resistivity (specific resistance) of the material. The reciprocal of resistivity is conductivity. Resistivity is a measure of the degree that a material opposes the flow of electric current, and conductivity is the degree that a material allows current to flow. A material which exhibits a high opposition to current flow is said to have a high resistivity. The same material could also be said to have a low conductivity.

The manner in which a semiconductor device behaves in an electronic circuit depends greatly on its resistivity, which can be controlled over a wide range. The value of resistivity (or conductivity) of a semiconductor depends on: the charge on each carrier; the concentration of current carriers (holes and electrons); and the carrier mobility (ease with which carriers may be moved).

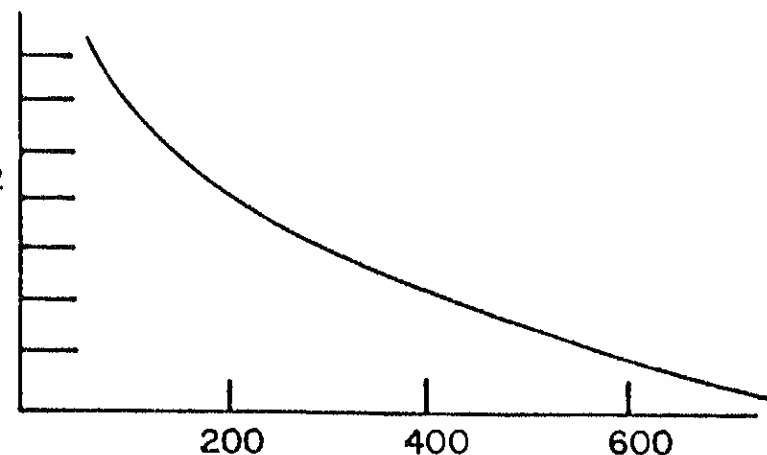
The charge on a hole is always +1 and the charge on a free electron is -1. These values cannot be changed. Thus, carrier concentration and carrier mobility are the properties that may be changed to alter resistivity. In general, it is desirable to make carrier mobility as high as possible. This leaves carrier concentration as

free electrons is equal to the number of value of the free-electron concentration concentration) in an intrinsic semiconductor the intrinsic carrier concentration. This increases exponentially with an increase in

B. Thermal generation and recombination

1. When a semiconductor is exposed to a temperature above absolute zero, some of the heat energy of the material may be acquired by an electron, which jumps from the valence band to the conduction band and leaving behind a hole. This produces two charge carriers: one hole and one electron. They are said to have been thermally generated. As long as the material is at a constant temperature, the free electrons and holes continue their continuous random motion even though there is no net current flow.
2. This may be likened to a swarm of bees flying in a field. Each bee moves rapidly from place to place, but if no new bees are arriving and none are leaving, the net flow of bees is zero, although there is continuous motion.
3. The rate at which hole-electron pairs are generated depends on the temperature and on the forbidden energy gap in the crystal. We recall that germanium has a smaller energy gap than silicon. Consequently, at a given temperature, the thermal generation rate will be higher in germanium than in silicon, because it takes less energy to excite an electron from germanium's valence band to the conduction band.
4. As a free electron moves randomly through the crystal structure, it may encounter a hole and combine with it. When the electron combines with the hole, the hole no longer exists and the electron is no longer free; hence, two carriers cease to exist. This process is called recombination.
5. The rate at which recombination takes place is proportional to the number of holes and free electrons in the material. When the rate at which the hole-electron pairs are generated is equal to the rate at which they recombine, the material is in thermal equilibrium.

vity will decrease (conductivity will increase) as more carriers are present to conduct current. Intrinsic carrier concentration increases with temperature, resistivity decreases, and conductivity increases. A typical plot of intrinsic resistivity versus temperature is shown in figure 15.



Variation of resistivity with temperature for intrinsic silicon.

Figure 15.

Intrinsic semiconductors, the number of free electrons is not equal to the number of holes. In N-type materials, each donor atom contributes a free electron but contributes a hole. The only holes present are produced by thermal generation. The thermally generated holes are called minority carriers. Similarly, in P-type materials, the only free electrons present are those thermally generated, and the number of electrons present is equal to the number created by the thermal generation plus the number generated by the donor impurity plus the number generated. The thermally generated electrons are called minority carriers.

increased, the concentration of thermal carriers may become comparable with that of impurity-produced carriers, and the resistivity becomes temperature-dependent. If the temperature of the semiconductor is increased to such an extent that thermally generated carriers greatly outnumber impurity-produced carriers, properties will be mainly dependent on the internally generated carriers, and the material will be intrinsic.

10. Resistivity of extrinsic germanium or silicon at a given temperature is determined almost completely by the amount of impurity present in the material. Within certain limits, any desired value of resistivity can be obtained by adding the correct amount of impurity during the formation of the crystal.

C. Mobility

1. It has been stated that mobility is a measure of the ease with which the carriers can be made to move through the material. It is measured as the rate of movement of a carrier (in centimeters per second) per unit electric field (1 volt per centimeter). Thus, the units are centimeters per second divided by volts per centimeter, or $\text{cm}^2/\text{volt-sec}$.
2. Although mobility does not appear to be directly related to resistivity considerations, it plays an important role in the behavior of semiconductors. In semiconductors, the mobility of the electrons is generally greater than the mobility of the holes; that is, it is easier to move a free electron in the conduction band than it is to move a bound electron in the valence band. (Keep in mind that the movement of electrons in the valence band from hole to hole brings about the movement of holes.) The fact that electrons can be made to move by the application of an electric field and the idea of "hole mobility" is not unreasonable.

ility	1,900	500	cm ² /volt-sec
c Resistivity	65	200,000	ohm-cm
ap	0.7	1.1	eV

intrinsic properties of Germanium
Silicon at room temperature.

TABLE 1.

several factors affect the carrier mobilities, one of the crystal structure through which the carrier move has the predominant effect. Any impurity or imperfections in the crystal lattice tend to hinder carrier motion. If the structure is perfectly crystalline, all atoms are in their proper places and no impurities are present. The carriers can move easily through the structure and mobility is high. However, if impurities exist in a crystal, the movement of carriers is retarded and mobility is reduced. The types of imperfections that can exist in a crystal structure are too numerous to delve into at this time. It might be said that one of the most important steps in the manufacture of semiconductor devices is the growth of crystals with as nearly perfect lattice structure as possible.

Temperature is another factor that affects mobility. At low temperatures, atoms in the crystal structure tend to stay in their regular places. As temperature is increased, energy is added to the crystal. Some of this energy is used to excite the electrons to the conduction band, but some of it is also given to the atomic cores, causing them to move very slightly. Although the cores do move away from their positions, they do vibrate about their position much as a violin string vibrates while leaving the violin. This vibration has the effect of impeding carrier motion.

D. Diffusion currents

1. It has been determined that if a voltage is applied across a piece of semiconductor material, the holes move toward the negative terminal and the electrons toward the positive terminal. The combined effect of this movement of holes and electrons constitutes a current.
2. It is possible for a current to flow in a semiconductor even in the absence of an applied voltage. This occurs when a concentration gradient exists in the material. A concentration gradient occurs when the concentration of one type of carrier is greater in one part of the semiconductor than it is in some other part.
3. When a concentration gradient of carriers (holes or free electrons) exists in a material, the carriers tend to move from the region of higher concentration toward the region of lower concentration. This movement is said to diffuse from the region of high concentration and the current produced by this movement is called a diffusion current.
4. Consider a small bar of P-type semiconductor in which the charges are evenly distributed throughout the length of the bar. The concentration of holes and electrons are in equilibrium and no gradient exists. Suppose that a large number of electrons (or minority carriers) is injected at one end of the bar. This process is accomplished will be discussed in PN junction theory.) These added minority carriers increase the concentration of electrons at the end where they are injected than in the rest of the bar. A concentration gradient exists. The excess electrons tend to move toward the other end of the bar, attempting to achieve a uniform distribution throughout the bar. This movement results in a diffusion current. The rate at which the electrons diffuse, and hence, the diffusion current depends on the value of the gradient and the mobility of the electrons.

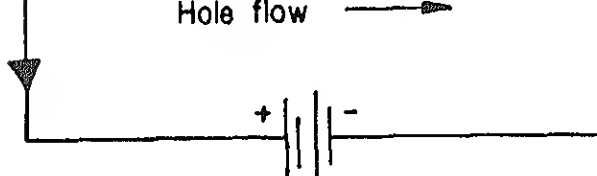
excess carriers disappear by recombination. The length of time required for the excess carriers to disappear by recombination is called the Lifetime of the excess carriers.

We have seen that two distinct things occur when excess minority carriers are injected into a material. The carriers diffuse and they recombine with the opposite-type carriers. Consider these two occurrences simultaneously. Imagine, again a high concentration of free electrons injected at one end of a P-type semiconductor bar. The electrons diffuse toward the other end of the bar and, at the same time, recombine with holes. As they move along the length of the bar, more and more of them disappear by recombination. Eventually, all of the excess electrons will disappear, but in the meantime they have moved along the bar; the distance the electrons move before they disappear is called the diffusion length of minority carriers. If excess holes are injected into an N-type material, the holes will undergo the same sort of process as free electrons.

We can see that the diffusion length of minority carriers in a material depends on how fast the carriers move and on how long they move before disappearing; that is, the diffusion length depends on mobility and lifetime.

3. Behavior of the PN junction

As we have seen, we have brought out in the information sheet, "Introduction to Semiconductors," that when a voltage is applied across a semiconductor, current flow is brought about as a result of holes moving toward the negative terminal and electrons moving toward the positive terminal (see figure



The flow of charges in a semiconductor due to an applied voltage.

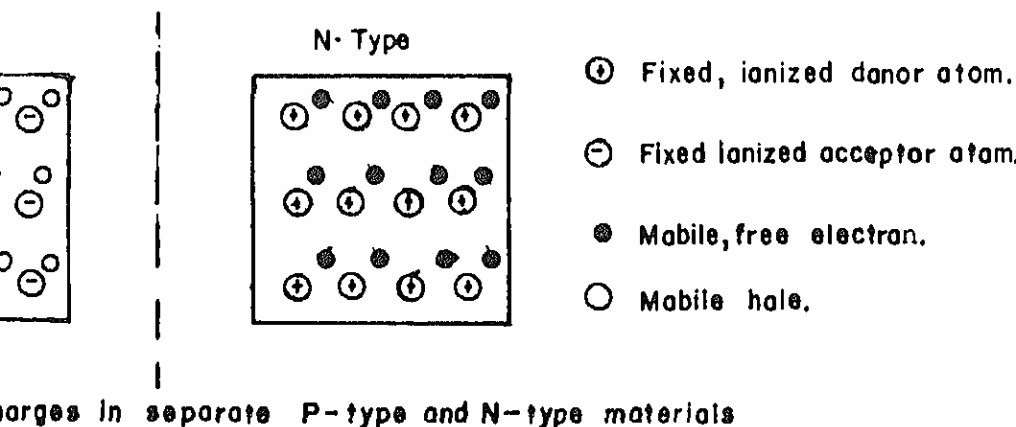
Figure 16.

The total current is the sum of the current hole flow and the electron flow. It is the total current. A second current may exist in a semiconductor. This current, called diffusion current, is the result of a gradient of a carrier concentration. A diffusion current may also be due to both hole and electron flow. The hole and electron flow is in opposite directions and the total diffusion current is the sum of the two.

- B. A material which contains an equal number of positive and negative charges is said to be electrically neutral. Objects which are electrically neutral do not have net electric charges. An ordinary atom is electrically neutral since it has as many negative charges (electrons) as positive charges (protons). When an atom loses an electron, it is left with a net positive charge and is called a positive ion. When an atom gains an extra electron, it has a net negative charge and is called a negative ion.
- C. A sample of semiconductor material is not electrically neutral since it is made up of atoms which are electrically neutral. Although a free electron is removed away from the atom (leaving a positive ion), the ion is inside the semiconductor material, the material remains electrically neutral. If a current flows through the material due to an applied voltage, electrons are entering the material at the positive terminal and leaving at the negative terminal. Electrons are entering (at the same rate as they are leaving) the terminal. The semiconductor remains electrically neutral during conduction when considered as a whole. However, if for some reason, a semiconductor is not electrically neutral, it will have a net charge.

and another object becomes negatively charged, a potential difference (or voltage) will exist between them.

an N-type semiconductor such as silicon. Each atom consists of a core with a net charge of $+4$ and four valence electrons, each with a charge of -1 . Thus, the atom is electrically neutral. Each donor atom has a core with a net charge of $+5$ and five valence electrons each with a charge of -1 . Only four of these valence electrons are in bonding with the silicon atoms. The fifth electron is free to wander around. As it moves away from its parent atom, it leaves behind a positive ion with a net charge of $+1$. The positive ion is not free to move, as it is fixed in the crystal structure. Thus, an N-type semiconductor is studded with immobile positive donor ions and mobile negative electrons. In a similar way, P-type silicon is regarded as a neutral material studded with immobile negative acceptor ions and mobile positive holes. Figure 17 illustrates the charge distribution in separate P-type and N-type materials.



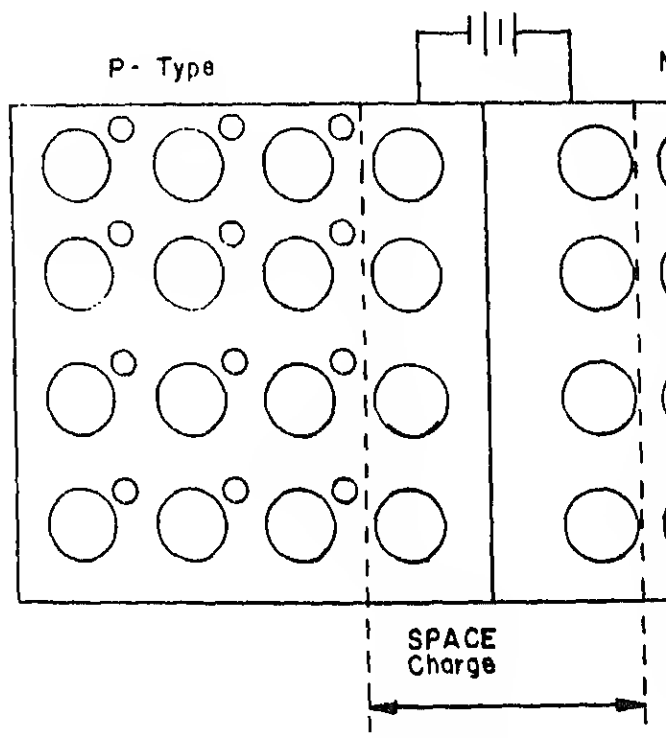
charges in separate P-type and N-type materials.

Figure 17.

silicon atoms are not shown and should be imagined as a continuous crystal structure over the whole background. The

it will allow current to flow through in direction.

- E. we now turn to the condition of the material when the junction is formed. (We shall take this as assuming that we can merely push the two materials together to form the junction.) A completely different set of conditions will now exist. In the P region there is a high concentration of holes. Since the hole concentration on the P side is so much greater than that on the N side, holes will diffuse into the N region. The diffusion is similar to the uniform distribution of ink in a glass of water after an ink drop has been added. In technical parlance, we say that a hole concentration gradient exists from the P to N region. Similarly, an electron concentration gradient exists from the N region and results in electron diffusion. See figure 18.



unneutralized positive ion. These unneutralized, immobile ions on each side of the junction are called uncovered charges, and the electric field between them can be conveniently represented by a battery placed across the junction as shown by the dashed lines in figure 18.

The holes that cross from the P to the N region recombine with electrons on the N side. Similarly, electrons from the N region recombine with holes on the P side. This flow of holes from the P to N side and electrons from the N to P side constitutes a recombination current across the junction. This recombination current does not, however, persist at some constant value. Instead it falls to some very low value in the vicinity of the junction. The uncovered negative ions on the P side start repelling the electrons from the N side while the wall of uncovered positive ions on the N side repels the holes from the P side. The battery in figure 18, therefore, represents the barrier potential set up by the uncovered charges, which inhibits the recombination currents. Thus, it seems that a condition of equilibrium is established between the diffusive potential of the concentration gradient, the barrier potential of the concentration gradient and the barrier potential of the uncovered charges.

If thermal agitation caused all the mobile carriers to have exactly the same kinetic energy, this simple explanation of equilibrium conditions at the barrier would suffice. However, the thermal energy imparted to the mobile charge carriers is randomly distributed. Statistically speaking, some holes and electrons have only a small amount of kinetic energy whereas others have a very large amount. Some of the high energy carriers will, from time to time, be capable of overcoming the barrier potential. If this were the only action, it would seem that the barrier height would keep increasing in an effort to compensate for those high-energy carriers that manage to hurdle it. Ultimately, we might expect the last of the mobile charges to cross the barrier leaving some large barrier potential.

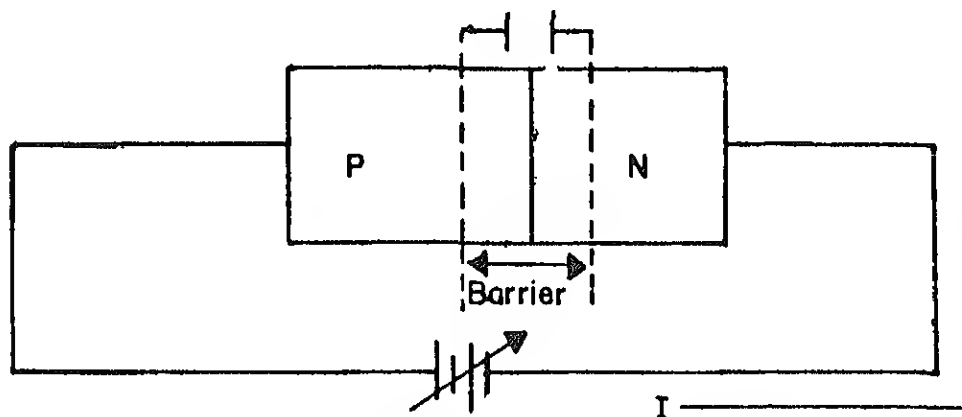
carrier, and it will have some average time of lifetime) before it combines with one of the n available. The lifetime of a minority carrier depends upon the number of surrounding majority which, in turn, is determined by the number of atoms introduced into the lattice.

- J. If this electron in the P region survives long drift into the vicinity of the junction, it will the influence of the electric field existing the direction of the field is such that the electron swept across the depletion region (region containing uncovered charges) since it is attracted by the positive ions on the N side. Another way of view this is to imagine the barrier battery in figure electrons from the P to the N side.
- K. By similar reasoning, we see that a thermally generated in the N material constitutes a minority carrier be swept across the depletion region from the N side. The flow of thermally generated minority across the junction is aided by the potential barrier.
- L. We now have a complete picture. With no external applied, the actual equilibrium conditions are There will be a net recombination current across the junction which consists of holes climbing the barrier P to the N side and electrons which climb the barrier in the opposite direction.
- M. At the same time, the breaking of covalent bonds creates a net thermally generated current because the minority carriers are swept across the barrier. The thermally generated current (minority) depends solely upon the barrier height. The net result is that the total junction current is zero which it must be, since shorting a PN junction with a piece of wire does not result in a current flow through the junction. The barrier height will assume a potential of such a value that it permits the recombination current to just balance the thermally generated current.

will be higher due to the increased concentration of donor and acceptor atoms. Overall, the barrier will become narrower.

Forward bias

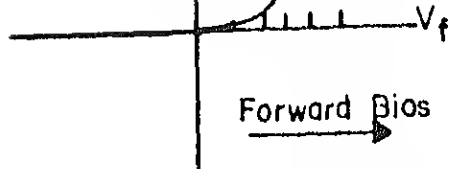
Consider that an external source of potential is connected to the PN junction, as illustrated in figure 19.



The PN junction with forward bias permits large amounts of current to flow.

Figure 19.

Placing the voltage source across the diode causes an electrical field which opposes the barrier potential (positive to P-type and negative to N-type material) established through the semiconductor. This is known as forward bias. The net effect is that the height of the barrier is reduced. For convenience, we might think of the external source as trying to push holes from the P to the N region and electrons from the N to the P region. The mechanism involved is, however, not one of pushing but merely controlling the net barrier potential. If we connect the source from one potential to a higher potential, we shall find that the current increases quite rapidly along some exponential curve. (Refer to figure 20.)

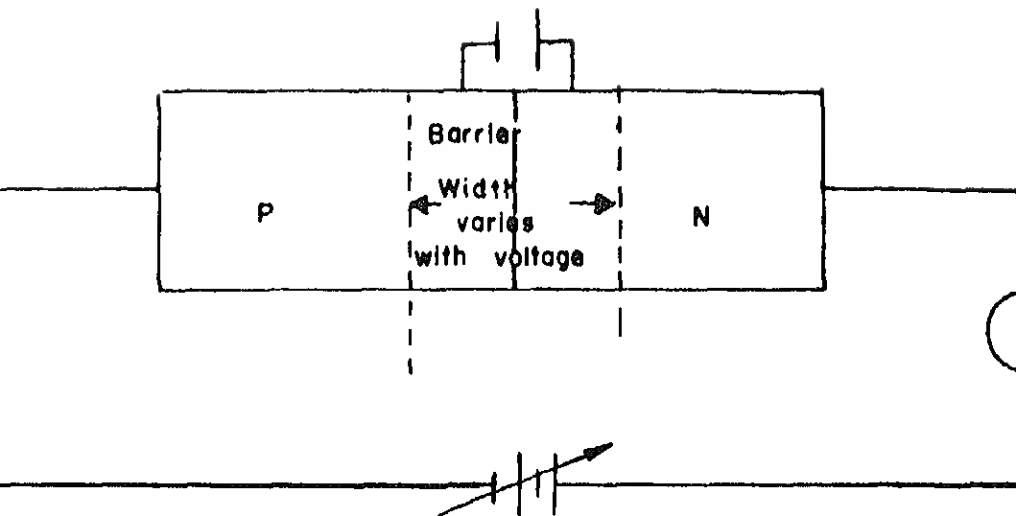


Forward bias characteristics.

Figure 20.

What is happening is that, in reducing the barrier the recombination current greatly increases because holes from the P region and electrons from the N cross the junction and recombine. The thermally current does not significantly change, for it is determined by the temperature and not the voltage in the forward bias case, recombination current is greater than thermally generated (minority) current.

- B. We might be tempted to think that putting a volt across the junction would annihilate the barrier and an enormous current flow. This does not occur because the current increases, more and more of the applied voltage is used up as a voltage drop across the bulk of the regions. The barrier can be reduced but not destroyed. An attempt to reduce the barrier excessively will result in the destruction of the semiconductor materials due to the heat dissipated in it.
- C. Once the internal barrier potential is greatly reduced by the applied forward bias voltage, the current becomes limited, only by the source resistance of the applied voltage source, the junction lead resistance, and the bulk resistance, and the bulk resistance of the semiconductor materials. The semiconductor material resistance is a function of the amount of doping, cross-sectional area and length. The bulk resistance (about 1 to 200 ohms) can cause a significant voltage drop; therefore, a current limiting resistor should be placed in series with the semiconductor under forward bias conditions.



Reverse bias connection.

Figure 21.

In this case, we see that the field established through the semiconductor by the external battery is such that it tends to oppose the internal potential barrier in keeping carriers from crossing to the junction. Mobile holes in the P region are drawn away from the junction toward the negative battery terminal. Mobile electrons in the N region are also drawn away from the junction toward the positive battery terminal. As more reverse bias that is applied, the wider the depletion region grows. If, as is usually the case, the two sides are unequally doped, the depletion region will extend further into the region of higher resistivity (material with least doping). This is easy to understand if we visualize the P and N regions as two resistors in series. A larger percentage of the applied voltage will appear across the larger resistor. This effect is important in transistors, for it results in a condition known as punch-through.

of reverse bias, the recombination current is essentially equal to the thermally generated currents (minority).

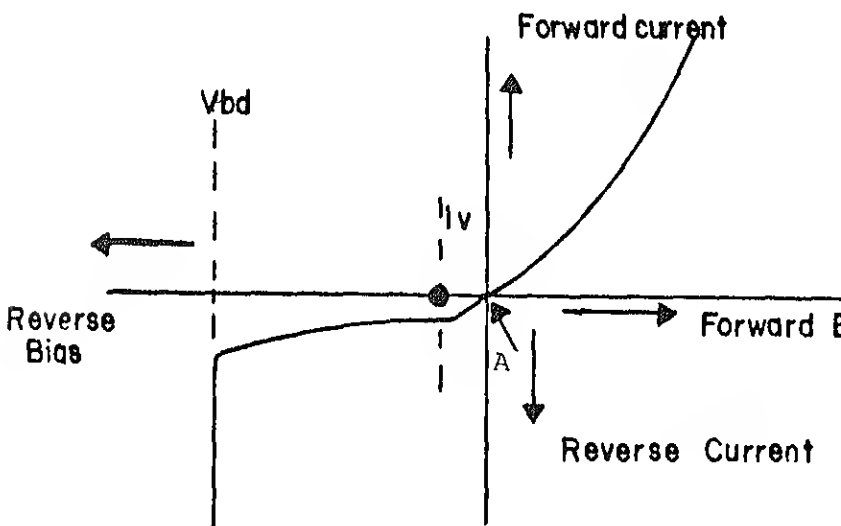


Figure 22.

- C. As the reverse voltage is increased, it seems reverse current remains constant since it is due to recombination and not voltage dependent. However, the fact that between -0.1 volt and V_{bd} (voltage breakdown) reverse current actually increases with reverse voltage. Such a characteristic should be expected if there is a leakage resistance in shunt with the junction. This resistance is due to dirt or other impurities on the junction and little understood surface effects which contribute to leakage resistance.

little a 100 microamperes at room temperature because the energy gap in silicon is higher than in germanium and therefore, at a given temperature, fewer electrons are excited out of covalent bonds into the conduction band. The value of minority current in silicon roughly doubles for every 6°C rise. Even though this is a more rapid increase than for germanium, the initial value is so low that silicon is generally preferred for high temperature work above 100°C .

Breakdown

As the reverse voltage across the junction is gradually increased, a point is reached where the reverse current starts to increase rapidly. This increase may be exceedingly abrupt in silicon junctions. The breakdown characteristic is indicated at V_{bd} (voltage breakdown) in figure 22. Notice that V_{bd} stays essentially constant for large variations in current. This is characteristic of a constant voltage source and is the basic principle on which the "voltage-regulating" or zener diodes operate.

The sudden increase in current may be the result of either of two mechanisms. First, if reverse bias is sufficiently increased, it is possible for the electrical field in the vicinity of the junction to become quite strong - so strong, in fact, that electrons are suddenly pulled out of covalent bonds when V_{bd} is reached. This phenomenon is known as zener breakdown.

The second and more common type of breakdown, called avalanche breakdown, is due to a secondary emission effect. Minority carriers produced by covalent bond breakup, are accelerated across the junction by the reverse bias. When the reverse bias approaches a critical value, the minority carriers have sufficient velocity to knock apart covalent bonds of atoms they collide with, and these in turn break other bonds, and so forth. The consequence is that a tremendous increase in the number of current carriers results which make the semiconductor material and junction appear to have a low resistance.

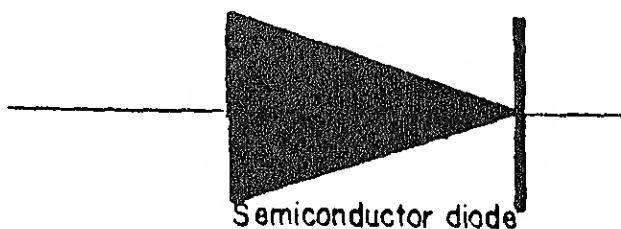
The diode reverse current in the breakdown region should be limited by an external resistance if reverse bias is to equal V_{bd} . The diode will not be harmed if the current

likened to the dielectric of a capacitor. bordering the depletion region have good because of the presence of charge carriers. be compared to the plates of a capacitor. of the depletion region is controlled by the reverse voltage, here is a capacitor depends upon the junction voltage. The varies with the method of fabrication of typical values range from 3 to 100 pF.

- B. In the recent years some manufacturers of devices have made voltage-sensitive capacitors available. They have found extensive applications in electronic equipment, particularly in the communications, as oscillator frequency control.

XII. Diode symbols

- A. Some facts hold true of all semiconductor diodes. These are stated here. (Refer to figure 23.)
- B. Figure 23 shows schematic representation of a diode. The arrowhead of the drawing will always be the anode. The anode will always be the P-type material. The cathode will always be the N-type material.
- C. In order to forward bias the diode, the anode must be positive with respect to the cathode. To reverse bias the diode, the anode must be negative with respect to the cathode.



Semiconductor diode.

Figure 23.

Kiver. Transistor and Integrated Electronics.
NY.: McGraw-Hill Book Company. 1972, Fourth Edition.

and Osterheld. Essentials of Radio-Electronics.
NY.: McGraw-Hill Book Company, Inc., 1961, Second

Metcalf, Lefler, and Williams. Modern Physics.
NY.: Holt, Rinehart, and Winston, Inc., 1968.

LINE:

structure

neral information

e atom

periodic chart

F. Energy levels of isolated atoms

bands

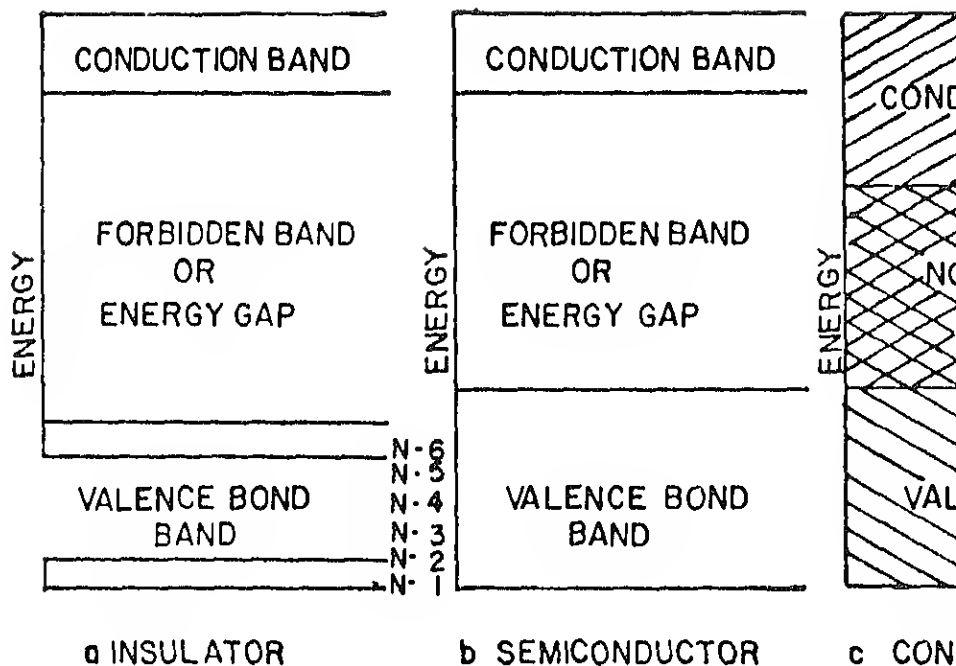
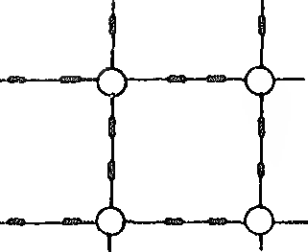
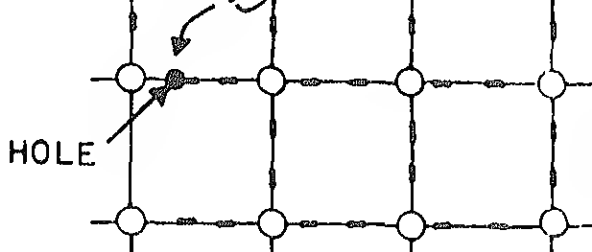


Figure 1. - Energy bands: (a) insulator (b) semiconductor (c) conductor

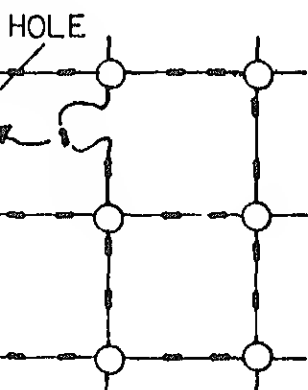
II. Intrinsic materials



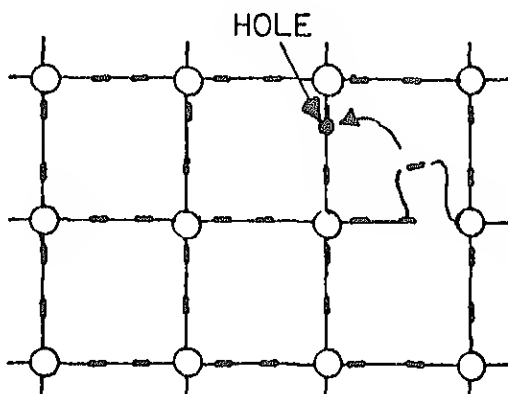
A



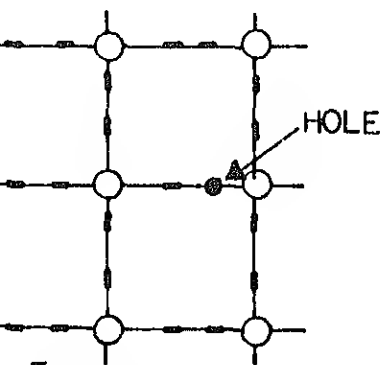
B



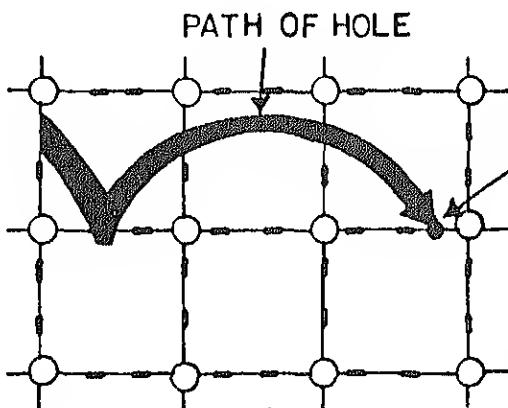
C



D



E



F

LEGEND

~ ELECTRON

○ HOLE

- ELECTRON-PAIR BOND

GERMANIUM CODE

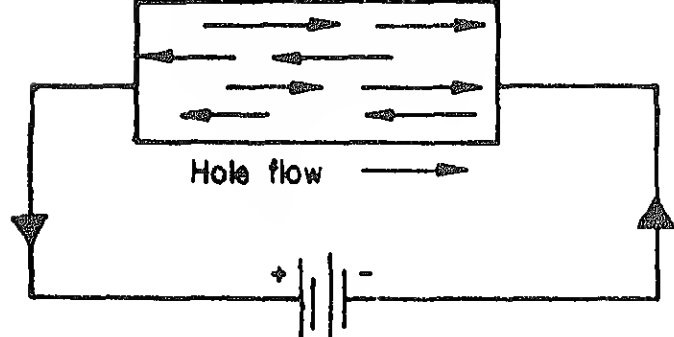
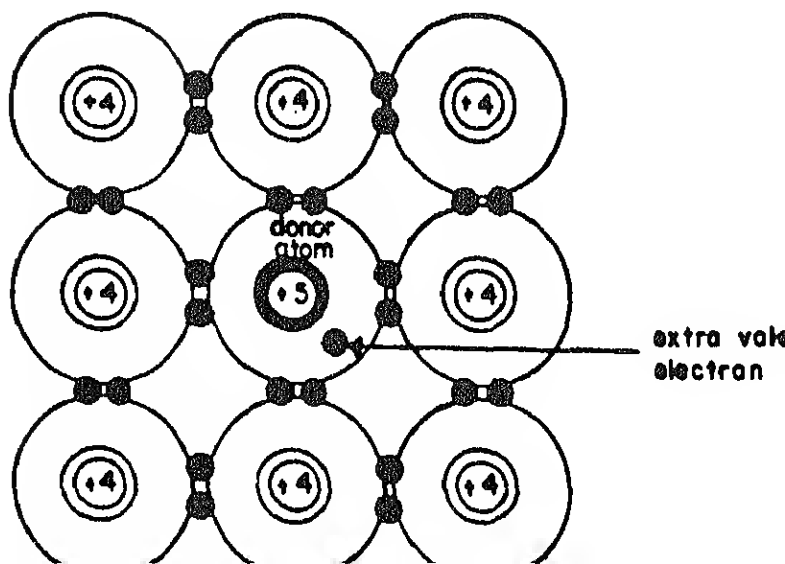


Figure 3.--Intrinsic conduction.

III. Extrinsic materials



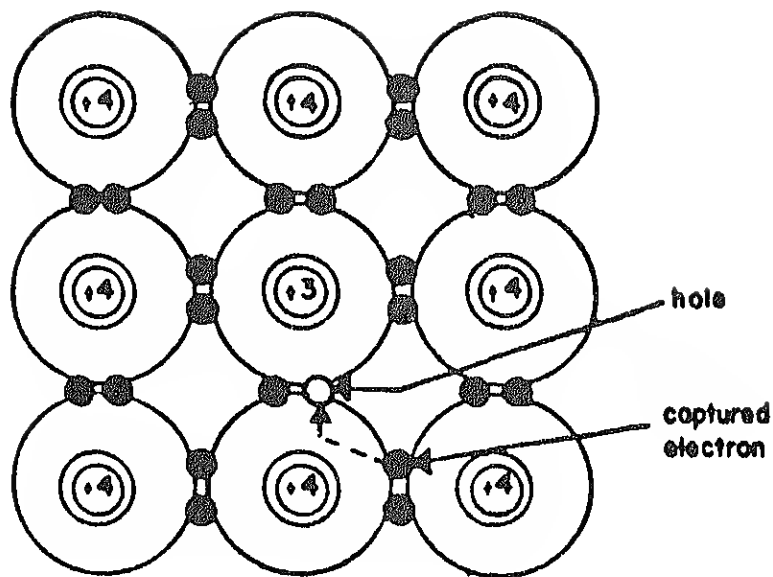
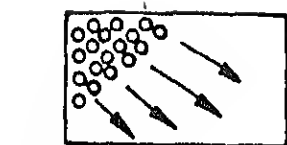
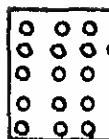


Figure 5.--P-type semiconductor material.

rical properties of semiconductors



Concentration
Gradient



Diffused

Figure 6.--Diffusion.

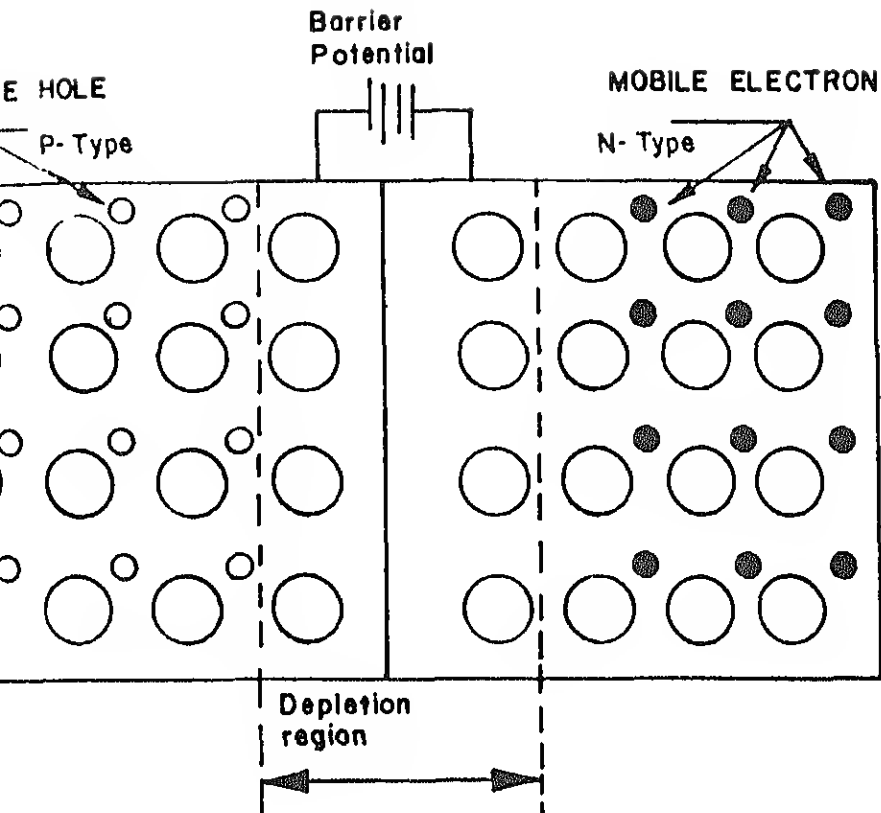


Figure 7.--Charges in an unbiased PN junction.

Reverse biased PN junctions

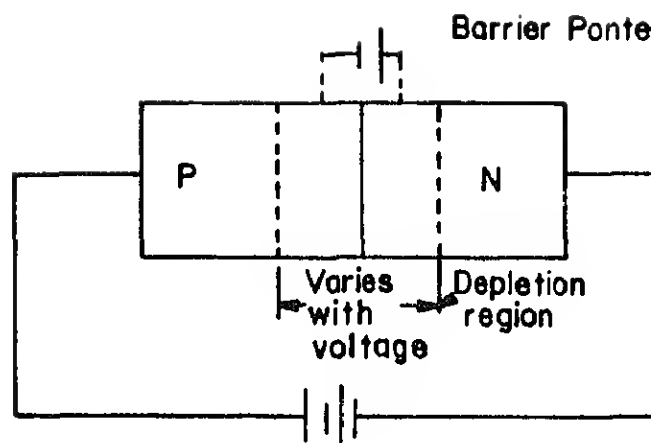


Figure 8.--Forward biased PN junction

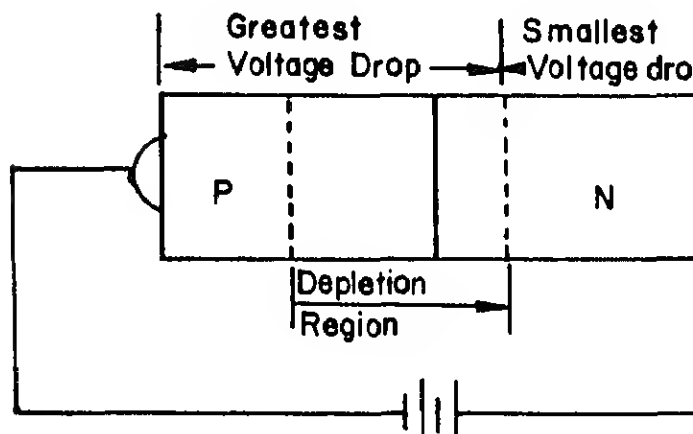


Figure 9.--Reversed bias PN junction

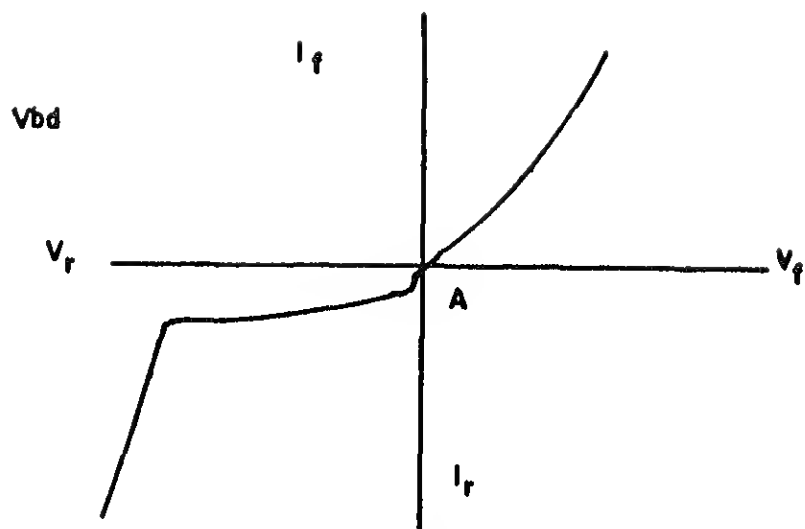


Figure 10.--Reverse bias versus reverse current.

Symbol and use

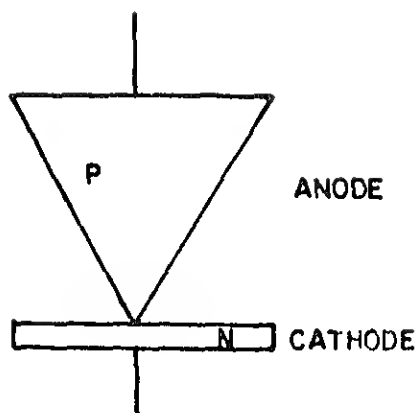


Figure 11. Diode symbology

the data sheet is for you to record the effects of reverse bias on a PN junction and the effects of changes on current flow through the junction.

d reverse-biased PN junction:

e table 1, entering d-c measurements in spaces d.

FORWARD BIAS	REVERSE BIAS	
I_B	$+V_{BE}$	I_B
V _____	+0.1 V	_____
V _____	+0.5 V	_____
V _____	+2.0 V	_____

TABLE 1

e the following graph, using the information obtained in table 1.

respect to minority current carrier

- (b) State the effect of removing heat from the junction with respect to minority current carrier concentration.
-

d. PN junction resistance calculations:

- (1) Forward-bias resistance at -0.2 V _____
(2) Reverse-bias resistance at $+2.0\text{ V}$ _____

e. Questions (Fill in the blanks.)

- (1) The major characteristic of a PN junction under forward bias is _____.
low/high resistance
- (2) When reversed-biased, the PN junction resistance is _____.
very low/high
- (3) When temperature increases, the amount of reverse saturation current _____.
increases/decreases
- (4) If not controlled, what effect will a change in temperature have on the PN junction?
-
-
-

Increased utilization of transistors, it has become
that you as technicians acquire an understanding of
The main purpose of this information sheet is to give
the fundamental principles of transistor action.

Electronic Circuits, NAVSHIPS 0967-00-0120, pp. 5-10 to 5-20.

Principles of Radio-Electronics, Slurzberg & Osterheld, McGraw-Hill,
, 1961 2nd Edition.

Electronic and Integrated Electronics, Kiver, McGraw-Hill Co.
1st Edition.

DEFINITION

General information

The advantages of using transistors are well known and need only cursory mention. Chief among the advantages are the small physical size and the extreme ruggedness of the transistor. Although designed to perform many of the functions of the vacuum tube, this device requires no filament power and operates with very low bias voltage.

Although the disadvantages of the transistor are steadily being diminished, present limitations to its use exist. There is still a basic limitation on the power handling capability, and the temperature dependence of its characteristics are often a challenge. The low resistance of transistors to radiation fields is another disadvantage.

With the increased utilization of transistors, it has become essential that technicians acquire an understanding of transistors. The main purpose of this information sheet is to draw forth the fundamental principles of transistor action.

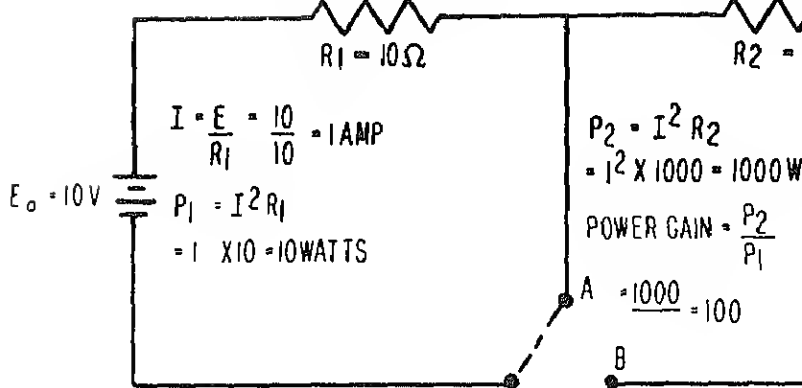


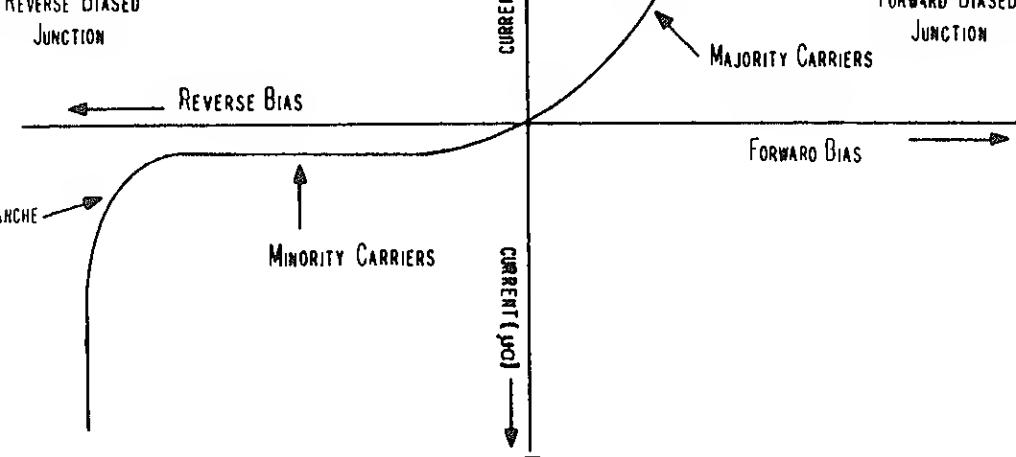
Figure 1 Transfer + Resistor = Transistor

Connecting resistor R_1 in series with the 10V source by placing the switch in position "A" would result in 1 ampere of current to flow, resulting in a power dissipation in R_1 of 10 watts. If, when throwing the switch to position "B" approximately the same 1 ampere is made to flow through R_2 , a hundredfold gain in power dissipation would result. If R_2 were in a position to offer a large portion of the dissipated power to an external load where useful work could be performed, the circuit in figure 1 could be considered an active circuit because of its ability to amplify power. The transfer of power across two resistance ratios gives rise to the concept of a transistor, and is the basic analogy of transistor action.

2. It is suggested that the reader review figure 1 before continuing, and keep in mind the analysis of transistor action that in its simplest form transistor action consists of:
 - a. Transferring approximately the same current through unequal resistances.
 - b. Utilizing the power developed across the larger resistance to perform some useful work.

C. Transistor analysis

1. In your previous lesson on junction diodes,



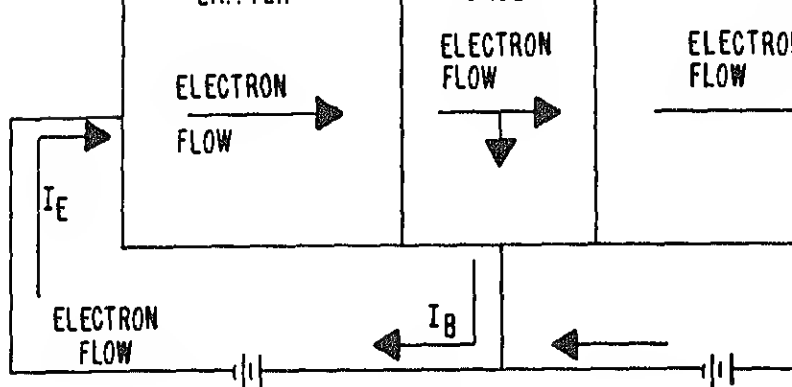
Conditions existing at a forward and reverse-biased PN junction.

Further observation of figure 2 reveals that the PN junction biased in the reverse direction is equivalent to a high resistance element (low current for a given voltage). Notice also that as the reverse bias voltage increases, the minority current remains relatively constant until avalanche is reached. Thus, it can be seen in figure 2 that:

- The amount of current flow through a forward-biased junction is primarily voltage dependent.
- The amount of current flow through a reverse-biased junction is not voltage dependent, but primarily dependent upon the number of minority carriers in P- and N-type materials.

Applied logic at this time will reveal the transistor action idea.

If a crystal containing two PN junctions were prepared, a signal could be introduced into one PN junction biased in the forward direction (low resistance) and extracted from the other PN junction biased in the reverse direction (high resistance). Such a device would transfer the signal current from a low resistance to a high resistance circuit.



NPN Transistor

Figure 3

3. Figure 3 depicts the basic model of trans. Notice that the N-type material labeled emitter is forward biased with respect to the P-type base, and the collector is reverse biased with respect to the base. Resistors R_1 and R_2 represent the emitter-base junction and collector-base junction respectively.
4. A basic analysis is as follows: with the emitter-base junction forward biased a current will flow across the junction. Some of this current will continue through the P-type base, and some will exit the P-type base to the forward-biased battery. In figure 2, it was stated that current flow across a PN junction under unbiased conditions is due to minority carrier injection. In the model, the electrons in the P-type base are the minority carriers. It was also stated that the current through a reverse-biased junction was dependent upon minority carriers and not the bias voltage. Thus, some percentage of the original carriers that crossed the base-emitter junction could cross the collector-base junction. Because the collector-base junction is reverse biased, it offers a high resistance to the electrons which cross the junction (represented by resistor R_2). Thus, we have transferred low resistance to a high resistance.

the high resistance. Thus, our problem is to minimize current flow out of the base lead in figure 3, and to cause most of the current that crosses the emitter-base junction to cross the collector-base junction as well.

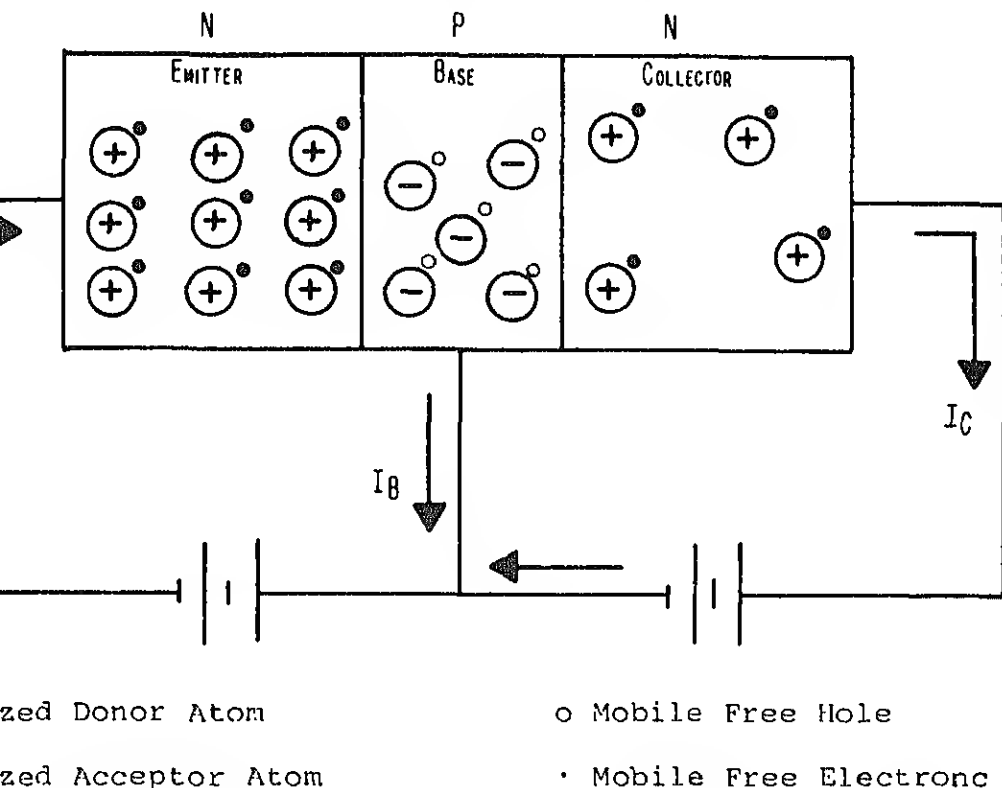


Figure 4

Figure 4 shows a schematic illustration of the charge distribution in the emitter, base, and collector regions of a transistor. The valence 4 atoms; i.e., silicon or germanium, are not shown and should be imagined as a continuous crystal structure over the whole background.

Notice that there are more carriers in the N-type emitter than in the P-type base, and that there are more carriers in the base than in the N-type collector (as a result

concentration of electrons and so will very soon recombine in the N-type region.

9. Re-examination of figure 4 will show that electrons which enter the P-type base region must travel into the region itself in order to recombine. The electrons in the base region are in equilibrium and spread themselves out in order to recombine with the holes as was defined in your lesson on PN junctions.
10. Each time an electron does recombine with a hole in the P-type base region, the region is no longer neutral, but takes on a negative charge (remember that an atom that takes on an excess electron is called a negative ion).
11. In order to regain its electrical balance, the base must give up an electron to the external circuit. This gives rise to a current called I_B (base current).
12. Again recall that our goal is to get as much of our emitter current (I_E) to flow through the collector region and become collector current (I_C). (See figure 1.) Figure 3 reveals that collector current is simply the emitter current (I_E) minus the base current (I_B).

$$I_C = I_E - I_B$$

Therefore, minimizing I_B will cause I_C to increase.

13. The action taken to minimize I_B should be understood at this time. As stated earlier, electrons must travel by diffusion through the base region. The distance they travel through the (base) region before they recombine with a hole is called their diffusion length. Now, let us introduce a second P-type material to the right of the base and, at the same time, make the base itself very thin. As the electrons diffuse through the center P-type (base) region, some of them will recombine with the process. However, if the width of the base is very small as compared to the diffusion length, only a few recombinations will occur.

for base junction are electrons in the P-type base material (minority carriers). Therefore, the collector-junction will appear as a forward bias, and the electrons will be swept across the junction. These excess electrons in the N-type collector will give it an excessive negative charge which it can easily give up to the external battery terminal in the form of I_C . Recall also that it is not the reverse bias voltage that is controlling the amount of electrons, but the forward biased emitter-base junction which controlled the electrons flowing into the base.

The process of causing majority carriers to cross over a junction and flow as minority carriers on the other side is called injection. This process describes precisely the action that takes place at the emitter-base junction.

The picture on transistor action is now complete, and can be described as three basic mechanisms:

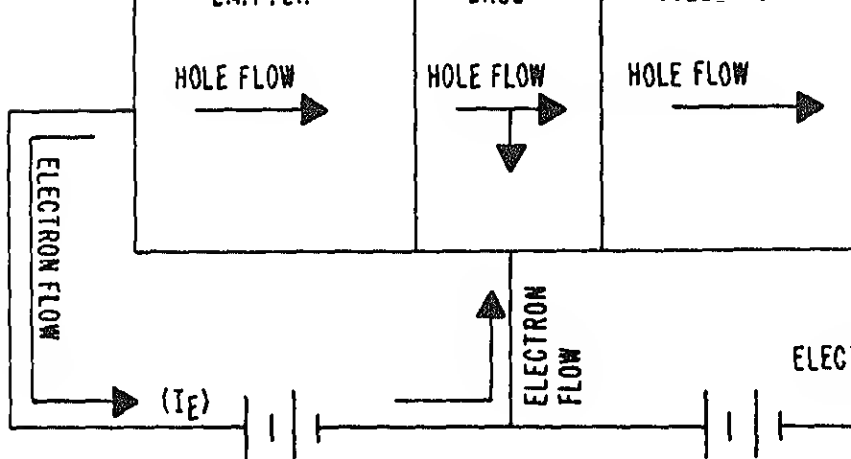
Injection - The process (under forward bias conditions) where majority carriers from the emitter are made to cross the emitter-base junction and flow as minority carriers in the base region.

Diffusion - The process by which the minority carriers (electrons) in the P-type base region travel (from an area of high carrier concentration to an area of low carrier concentration).

Collection - The process of causing minority carriers (electrons in a P-type material) to become majority carriers (electrons in an N-type material) and giving them up to the external circuit.

In the transistor model, external current was supported by majority carriers (electrons) in the transistor itself. Electrons are majority carriers in both the emitter and collector, both of which are N-type carriers. The three mechanisms of transistor action can be achieved in an NPN transistor.

Figure 5 depicts the basic model of a transistor that in this configuration is made of both P-type material



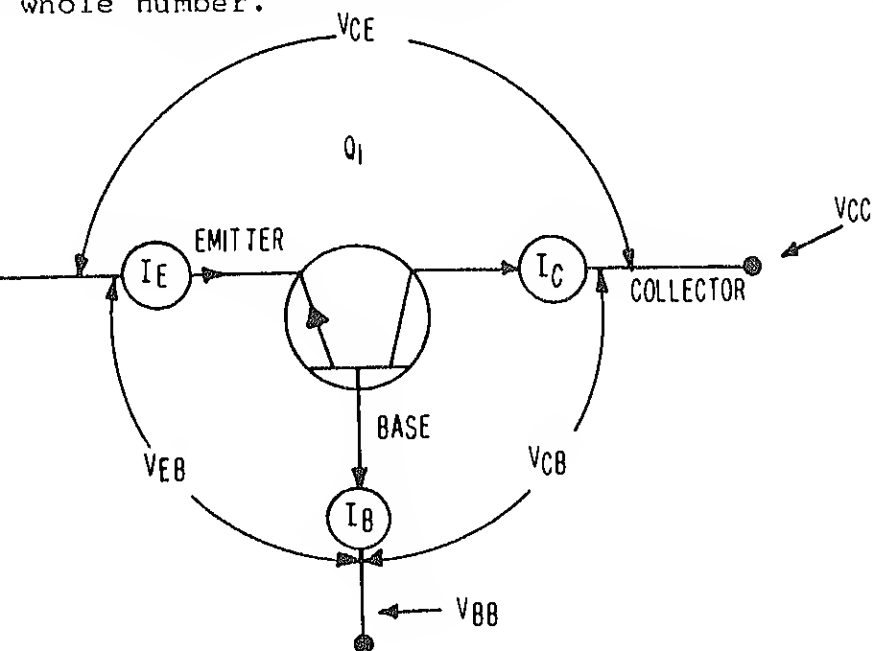
PNP Transistor

Figure 5

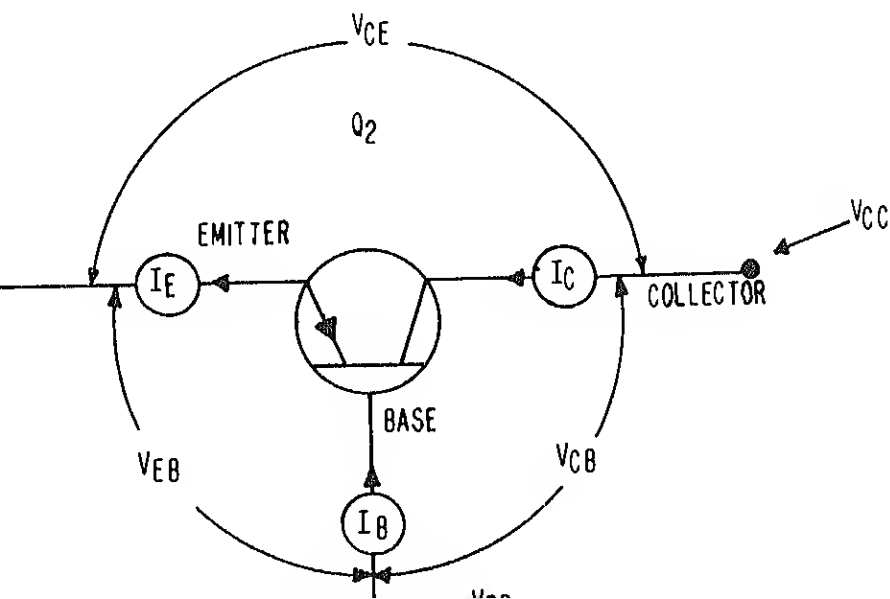
19. As forward bias is applied to the emitter-base junction, holes are accelerated across the emitter-base junction. Once the holes enter the base region, they act as minority carriers (holes in an N-type material). Some of these holes recombine with some of the excess electrons in the base, creating positive ions. In order to maintain electrical balance, the base will readily accept an electron from the external circuit for each hole that recombines, which is created by an electron-hole recombination process. However, in order to reduce the number of holes that recombine in the base, the base is made very thin and is more heavily doped just as in the case of an NPN transistor (figure 4). The holes that do not recombine in the base region continue to travel by the drift process; i.e., from an area of high carrier concentration to an area of lower carrier concentration. The holes which diffuse near the reverse-biased collector-base junction are swept across the junction by the electric field. Once these holes enter the collector region, the collector must accept them from the external circuit in order to achieve electrical balance.

20. Thus, the external circuit current (electron current) is supported by internal minority carrier current.

reference designations and schematic symbols for
 stors are shown in figure 6 (A) and (B). The letter
 n of the reference designation is Q. The number may
 whole number.



transistor



2. In the PNP transistor (B, figure 6), the to-collector current carrier in the device is holes. For holes to flow internally from emitter to collector, the collector must be negative with respect to the emitter. In the external circuit, the collector is connected to emitter opposite to the direction of the emitter arrow.
3. The following generalizations are helpful in determining the behavior of transistor circuitry. These apply to a transistor that is operated as a common-emitter amplifier.
 - a. The first letter of the type of transistor indicates the polarity of the emitter voltage with respect to the base. A PNP transistor has positive voltage applied to the emitter ($+V_{EE}$). An NPN transistor has negative voltage applied to the emitter ($-V_{EE}$).
 - b. The second letter of the type of transistor indicates the polarity of the collector voltage with respect to the base. A PNP transistor has negative voltage applied to the collector ($-V_{CC}$). An NPN transistor has positive d-c voltage applied to the collector ($+V_{CC}$).
 - c. The first and second letter of the type of transistor indicate the relative polarities between the emitter and the collector respectively. In a PNP transistor, the emitter is positive with respect to the collector; the collector is negative with respect to the emitter ($-V_{CE}$). In an NPN transistor, the emitter is negative with respect to the collector; the collector is positive with respect to the emitter ($+V_{CE}$).
 - d. The d-c electron current direction is opposite to the direction of the arrow on the emitter.
 - e. If the electrons flow into or out of the emitter, the collector current is respectively (I_C).
 - f. The base current is always equal to the emitter current minus the collector current ($I_B = I_E - I_C$).

negative with respect to the base (V_{CB}). In an NPN transistor, the collector is positive with respect to the base ($+V_{CB}$).

input voltage that aids (increases) the forward bias increases the emitter and collector currents.

input voltage that opposes (decreases) the forward bias decreases the emitter and collector currents.

The reverse bias voltage (V_{CB}) is normally much greater than the forward bias voltage (V_{BE}) in a transistor. Typical values of V_{CB} range from 3 to 8 volts d-c. Typical values of V_{BE} are .2 volts d-c for germanium and .6 volts d-c for silicon crystals.

Configurations

A transistor is a three-element, three lead device, capable of using it in any of three different, useful configurations. The identification of each of these basic circuits is derived from the element "common" to input and output. The three possible connections are: common-base, common-emitter, and common-collector. An often used variation is "grounded" emitter, "grounded" base, etc., where the common element is usually returned to the signal source in a circuit.

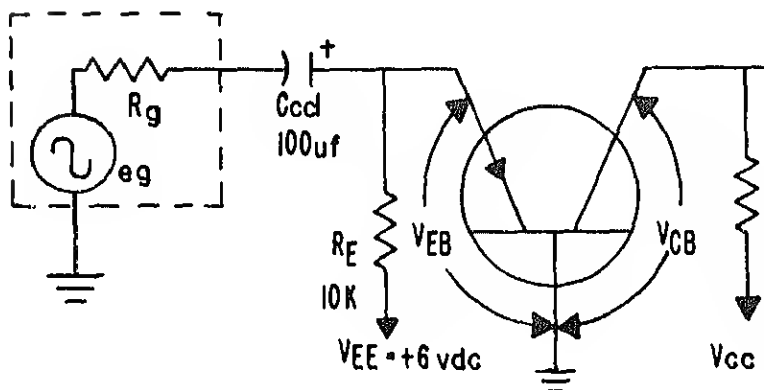
The amplifier

It is convenient to start a detailed examination with the common-base amplifier, which is normally considered to be the "reference amplifier" for any comparisons of the three basic amplifier configurations.

Figure 7 is a schematic drawing of a common-base amplifier of the PNP type. Notice that the input is supplied between the emitter and base. Thus, the base is common to the input and output. In "transistor symbology" you will find some general rules to follow when analyzing transistor circuits. Following these rules, you will find proper operation that V_{EE} must be a positive voltage and V_{CC} a negative voltage for proper biasing.

source, and R_C is chosen to provide the desired gain. The reverse-bias voltage (V_{CB}) is $I_C R_C$. The reverse bias voltage will normally be (3 to 6 volts) as compared to the forward

4. Let us analyze the amplifier under dynamic conditions.



Common-Base Amplifier

Figure 7

currents. The decreasing collector current will cause a voltage drop across R_C , making the collector more negative. ($V_{CB} = V_{CC} - I_C R_C$). Thus, a positive input signal produces a negative-going output signal. During the positive half-cycle of the input signal, the emitter will be driven more positive than its static (no signal) conditions. This will cause the current in the emitter and collector to increase, causing the voltage drop across R_C to increase. Note that the polarity of the input signal is opposite the polarity of the output signal.

For the output, a load resistor (R_C of 1000 ohms) is used. When the current is concerned, there is less at the collector than at the emitter. $I_C = I_E$. The difference (I_B) is normally 1 or 2 percent of the emitter current in the device (I_E).

The ratio of the change in the output current (I_C) to the change in the input current (I_E), or $\frac{I_C}{I_E}$, is referred to as the "current gain" (β) of the transistor. Thus, the current gain of this amplifier arrangement is less than 1, and this may lead one to believe that the circuit has little voltage gain. This is not true; a large voltage gain may be achieved because the output load resistance is much greater than the input resistance. Thus, if we assume an input resistance of 50 ohms (the forward biased emitter-base junction) and utilize a 1000 ohm load resistance, the voltage gain (input to output) is:

$$A_{v_{in}} = \frac{\Delta E_{out}}{\Delta E_{in}} = \frac{\Delta I_C R_C}{\Delta I_E R_{in}}$$

0.98 for a typical value

$$A_{v_{in}} = \frac{\Delta E_{out}}{\Delta E_{in}} = 0.98 \times \frac{1000}{50}$$

$$= \frac{\Delta I_C^2 R_C}{\Delta I_E^2 R_{in}}$$

$$= .98^2 \times 20$$

$$= .96 \times 20$$

$$\text{Power gain} = 19.2$$

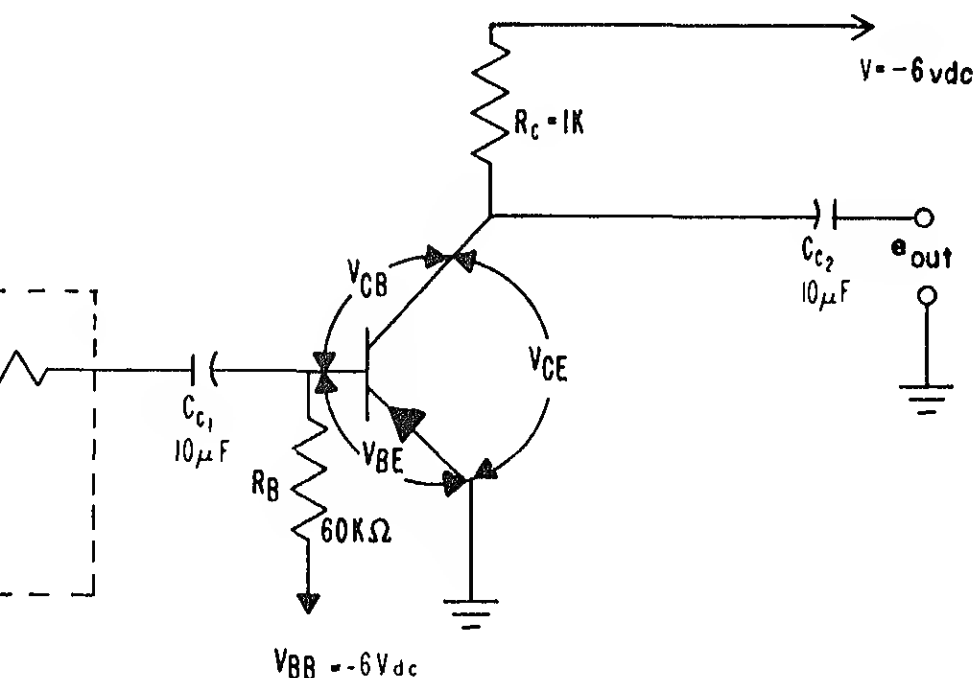
8. In the input impedance of a transistor in the common-emitter configuration is very low because of the forward-biased emitter-base junction. The output impedance is the load resistor and look into the collector. It is high, on the order of 1 to 2 megohms. However, if we connect a load resistor of 1000 ohms, then the value of the output impedance since it compares with the 1 to 2 megohms with which it is basically the same. It is well for the reader to keep this distinction in mind because reference is often made in literature to the output impedance of the common-base arrangement without the load resistor. Once a much smaller resistance is connected to the collector, it essentially determines the output impedance.
9. In summary, the characteristics of the common-emitter amplifier configuration are:
 - a. No phase inversion between input and output.
 - b. Low input resistance because of forward-biased (V_{EB}) typical values 50-100 ohms.
 - c. The output signal sees a reverse-biased collector-base junction.
 - (1) Typical values 1-2 megohms.
 - (2) In a practical circuit, R_C shunts the collector-base resistance of the transistor.
 - d. The output to input resistance ratio is high, which leads to a very high voltage gain.

The input signal is applied between the emitter and the base.

The output signal is taken between the collector and the base.

The base is "common" to both the input and the output.

Common-emitter amplifier



Common-Emitter Amplifier

Figure 8

volts (V_{BE}). Current flows through the base resistor R_B , a 60 k-ohm resistor. I_B (approximately equal to $\frac{V_{BE}}{R_B}$) will develop a forward bias voltage across the base emitter junction (V_{BE}).

- As is normally the case, this forward bias is very small. V_{CC} is the collector supply source chosen to provide the desired voltage gain. The collector bias voltage (V_{CB}) is equal to $V_{CC} - I_C R_C - V_{BE}$.
- Again, let us analyze the amplifier under dynamic conditions. As the incoming signal goes negative (decreases) the normal negative bias between base and emitter (V_{BE}). An input voltage that aids the normal bias will increase the emitter and collector current. Increasing collector current will increase the voltage across R_C , making the collector potential more positive ($V_C = V_{CC} - I_C R_C$). Thus, a negative-going input signal produces a positive-going output signal. During the positive half-cycle of the input signal, the collector is driven more positive than it was under static conditions. This will decrease the current through the emitter and collector leads causing the voltage across R_C to decrease. This decreased voltage drop across R_C will cause V_C to become more negative. Thus, in the common-emitter amplifier polarity inversion between input and output.
- For the output, a load resistor of 1000 ohms is utilized to compare the characteristics of the common-emitter with those of the common-base amplifier.
- Since the input signal is applied to the base of the common-emitter amplifier, it is the variations in the base signals on the base which control the collector current. As stated previously, $I_C = I_E - I_B$. It was noted that the difference in I_E and I_C is I_B , which is a small percent of the total current (I_E). In fact, the amplifier was intentionally designed to minimize I_B by using a small region, heavily doped emitter. Thus, it follows that minute variations of base current produce large variations in collector current. If we assume

current gain in the common-emitter amplifier is

$$\text{current gain} = \frac{\Delta I_C}{\Delta I_B}$$

If $\frac{\Delta I_C}{\Delta I_B}$ is called Beta (β). In our amplifier the

would be .1 mA, while the collector received
substituting these values, we obtain

$$\frac{\text{mA}}{\text{mA}}$$

sizeable current gain is obtained, in contrast
loss incurred in the common-base amplifier.
Resistance of the common-emitter amplifier is
higher than the input resistance of the
amplifier. As was the case with the
amplifier, the input is applied across a
biased junction (V_{BE}); however, the current flow
junction (I_B) is quite small as compared to the
flow through the common-base forward-biased

$$\frac{V_{BE}}{I_B}$$

$$\text{values} = \frac{.2 \text{ volts}}{.1 \text{ mA}} = 2 \text{ k-ohms}$$

impedance, looking into the collector, before
connected, is about 500,000 ohms. This is
less than the value presented by the common-base

$$\frac{\Delta I_B}{R_{in}}$$

$$= 49 \times \frac{1000}{2000}$$

$$= 24.5$$

8. This is somewhat larger than the voltage gain the common-base amplifier. The difference is much; however, power gain is considerably better.

$$\text{Power gain} = \frac{\Delta I_C^2 R_L}{\Delta I_B^2 R_{in}}$$

$$= 49^2 \times .5$$

$$= 1200.5$$

9. In summary, the characteristics of the common-emitter amplifier are:
- There is a polarity inversion between the input and output.
 - Higher input resistance than the CB amplifier, value 2 k-ohms.
 - The output resistance of the common-emitter amplifier is less than that of the common-base amplifier. R_C will shunt the output just as it did the common-base amplifier.
 - The output to input resistance ratio is much greater, which leads to a good voltage gain.
 - There is a good current gain in the common-emitter configuration.

$$\frac{\Delta I_C}{\Delta I_B} = \beta$$

$$(c) \beta = \frac{I_C}{I_E - I_C}$$

(2) Dividing denominator and numerator by I_E

$$\frac{\frac{I_C}{I_E}}{\frac{I_E}{I_E} - \frac{I_C}{I_E}}$$

(3) However, $\frac{\Delta I_C}{\Delta I_E} = \alpha$

By substitution; $\beta = \frac{\alpha}{1 - \alpha}$

(1) It can be seen that by keeping the recombination currents in the base circuit very low, alpha approaches unity.

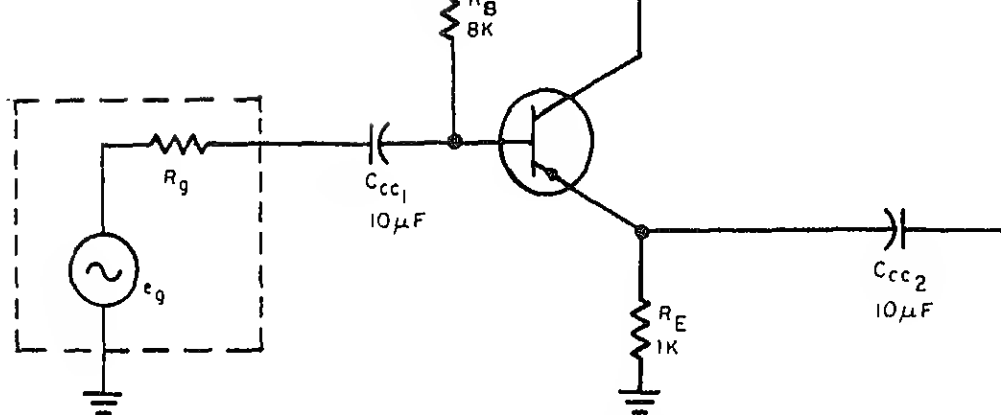
(2) As α approaches unity, β will approach infinity.

There is a very high power gain in the common-emitter amplifier.

is because of its higher current gains, power gains, a relatively close input-to-output impedance ratio (1 to 1 in our example), that the common-emitter amplifier configuration is the most popular configuration in transistor circuits.

Collector Amplifier

final transistor amplifier circuit arrangement is the common-collector. This is shown schematically in figure 8. Note that the collector of the transistor is not at d-c ground and since the collector still requires a $-V_{CC}$. Note all bias polarities. They are the same polarities as were required for the common-emitter amplifier in figure 8.



Common-Collector Amplifier

Figure 9

2. The input signal will be developed across the base collector junction (the collector is the common element and the output signal will be developed across the emitter resistor R_E . Thus, in the common-collector amplifier, the input is applied to the base and the output is taken from the emitter with the collector the common element.
3. Analyzing the amplifier under dynamic conditions, when an incoming signal goes negative, it will aid the normal negative bias between base and emitter (V_{BE}). An increase in forward bias will increase the emitter and collector currents.
4. When the increasing emitter current will increase the voltage drop across the emitter resistor R_E (negative to positive from the top of R_E). Therefore, a negative-going input signal will develop a negative-going output signal. During the positive half-cycle of the input signal, the base will be driven more positive than it was with no signal. This will decrease forward bias, and will lead to decreasing current in the collector and emitter. A decreased emitter current will decrease the voltage drop across the emitter resistor, causing the output signal to go in the positive direction. Thus, in the common-collector configuration, there is no polarity inversion between input and output. The current gain of a common-collector amplifier is approximately equal to the current gain of a common-emitter amplifier.

$$= \frac{I_C}{I_B} + \frac{I_B}{I_B}$$

$$= \beta + 1$$

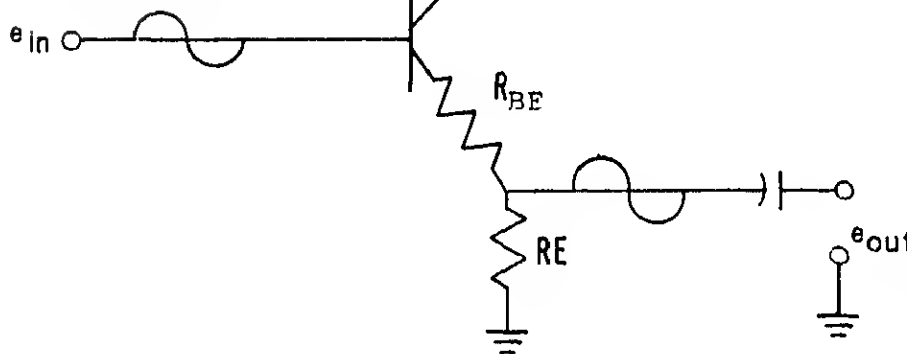
of the change in output current, I_E , to the

ent, I_B , or $\frac{\Delta I_E}{\Delta I_B}$ is referred to as "gamma", γ .

ge gain of the amplifier is always less than 1, generally it is not much less than 1. The emitter envelops the output signal which will be in the ity as the input.

seen in figure 10, as the input signal goes (which would increase forward bias), the output also goes negative, which tries to reduce the bias. The actual difference between the input and would be the voltage dropped across the forward tion R_{BE} .

s resistance is very low, the output voltage will ual the input voltage. In short, what we have is le degeneration.



Input Resistance of the Common-Collector Amplifier

Figure 10

8. Power gain is achieved in the stage because of current gain, but the gain is less than it is in common-base or common-emitter characteristics.
9. In summary, the characteristics of the common-collector amplifier are:
 - a. There is no polarity inversion between the input and the output. For this reason the common-collector amplifier is frequently referred to as an emitter-follower.
 - b. Highest input resistance of the three possible configurations. The input is applied between the base and emitter, across the collector-base junction which is reverse biased.
 - c. The output resistance is very low in the common-collector configuration, the emitter resistor is in series with the load.
 - d. The voltage gain is less than 1. You may be asked why use a common-collector stage if the voltage gain is less than unity? Because the input resistance is high (approximately 100 k-ohms) and the output resistance quite low (approximately the size of the emitter resistor). Use the common-collector similar to a transformer that it can be used to transform (step down) the impedance.

e. There is a very high current gain in the common-collector configuration

$$\frac{\Delta I_E}{\Delta I_B} = \text{Gamma} = \gamma = (\beta + 1)$$

f. There is a very low power gain in the common-collector amplifier because of the low voltage gain, and low output resistance.

$$p = \frac{E^2}{R}$$

Comparisons of amplifier configurations

Figure 11 is a table of comparisons of the three amplifier configurations. Note that there are no comparative values given for current gains, voltage gains, or power gains. The reason is quite simple. The actual values of current gains (current, voltage, and power) are dependent on the size of the load and the input resistance.

	COMMON BASE (CB)	COMMON EMITTER (CE)	COMMON COLLECTOR (CC)
TRANSISTOR DEVICE INDICATE IN CURRENT AIDS NOT	$h_{FB} = I_C / I_E$ $I_C = I_E - I_B$	$h_{FE} = \beta = I_C / I_B$ $I_C = I_E - I_B$	$h_{FC} = I_E / I_B$
TRANSISTOR CIRCUITS SIGNAL AND LOAD (R_L)			
GAIN * GAIN * GAIN * PEACANCE * MPEDANCE * INVERSION	YES YES (APPROX. SAME CE) NO (LESS THAN UNITY) LOWEST ($\approx 50 \Omega$) HIGHEST ($\approx 1.0 \text{ MEG.}$) NO	YES (HIGHEST) YES YES INTERMEDIATE ($\approx 10K$) INTERMEDIATE ($\approx 50K$) YES	YES NO (LESS THAN YES HIGHEST (≈ 300) LOWEST (≈ 300) NO
EQUIVALENT TRANSISTOR			

operation, or service of electronic equipment is the transistor manual. Here, we find the mechanical and electrical specifications for each type of transistor in similar fashion, equivalent data is published by the manufacturers for each of their products. Transistor manufacturers' sheets contain the specifications for a particular transistor, including maximum ratings, characteristic curves, and physical outline.

1. A typical specification sheet is shown in figure 13. The various sections of the specification numbered 1 to 3, and the appropriate explanation will be discussed.
2. We will not cover each specification at this time to the degree of knowledge on transistors required in later lessons, as your knowledge of transistors increases, you will be able to interpret all data given by the manufacturer in his specification.
 - a. The lead paragraph is a general description of the device and usually contains three specific items of information: in this instance, an alloy-junction germanium PNP transistor, a few major applications, computers and switching applications, and special features such as standard size and type package.
 - b. The absolute maximum ratings which must not be exceeded. To exceed them may cause device failure. The dissipation of a transistor is generally limited by the junction temperature (T_j). Therefore, the higher the temperature of the air surrounding the transistor (T_A = ambient temperature), the less the device dissipates. A factor which indicates how much the transistor must be derated for each increase in ambient temperature is usually given. Note that the 2N404 (given on the specification sheet) can dissipate 150 mW at a T_A of 25°. Applying the given derating factor of 2.5 degree increase in ambient temperature, we find the power dissipation will drop to zero mW. This, then, is the maximum operating temperature of the transistor.

$$\frac{\Delta I_C}{\Delta I_B} = 135.$$



Close parameter control and the JEDEC TO-5 welded package ensure device reliability and stable characteristics

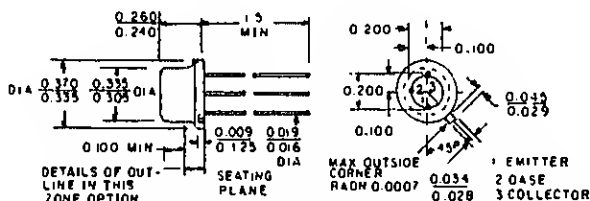
Environmental tests

To ensure maximum reliability, stability, and long life, all units are aged at 100°C for 100 hours minimum prior to electrical characterization. All transistors are thoroughly tested for complete adherence to design characteristics. In addition, continuous qualification tests are made comprising temperature cycling, humidity cycling, shock and vacuum leak testing under rigid in-process control procedures.

Mechanical data

Metal case with glass-to-metal hermetic seal between case and leads. Unit weight is approximately 0.025 grams. These units meet JEDEC TO-5 registration.

All leads insulated from the case.



ALL DIMENSIONS IN INCHES

Maximum ratings at 25°C free-air temperature (unless otherwise noted)

	2N404	2N404A
Collector-Base Voltage	25v	40v
Collector-Emitter Voltage (see note 1)	24v	35v
Emitter-Base Voltage	12v	25v
Collector Current	100ma	150ma
Emitter Current	100ma	150ma
Total Device Dissipation (see note 2)	150mw	150mw
Operating Collector Junction Temperature	85°C	100°C
Storage Temperature Range	-65°C to +100°C	-65°C to +100°C

NOTES: 1. Punch through voltage

2. For 2N404 derate linearly to 85°C free-air temperature at the rate of 2.5 mw/°C

For 2N404A derate linearly to 100°C free-air temperature at the rate of 2.0 mw/°C

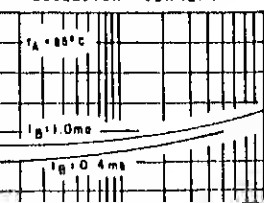
* Indicates JEDEC registered data.

The maximum power dissipation at 25°C case temperature is 300mw.

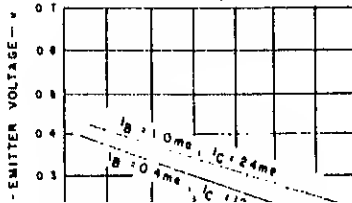
CURRENT		$T_A = 85^\circ\text{C}$		$T_A = 85^\circ\text{C}$		$T_A = 85^\circ\text{C}$		$T_A = 85^\circ\text{C}$		$T_A = 85^\circ\text{C}$	
VEBO	EMITTER-BASE BREAKDOWN VOLTAGE	$V_{EB} = -8\text{V}, I_C = 0$	—	—	—	—	—	—	—	—	μA
VCBO	COLLECTOR-BASE BREAKDOWN VOLTAGE	$I_C = 20\text{mA}, I_E = 0$	—	—	—	—	—	—	—	—	μA
VEBO	EMITTER-BASE BREAKDOWN VOLTAGE	$I_E = -20\text{mA}, I_C = 0$	—	—	—	—	—	—	—	—	μA
F ₀	DC FORWARD CURRENT TRANSFER RATIO	$V_{CE} = -0.1\text{V}, I_C = 10\text{mA}$	80	100	—	80	100	—	—	—	—
		$V_{CE} = -80\text{V}, I_C = 10\text{mA}$	24	110	—	24	110	—	—	—	—
DE	BASE-EMITTER VOLTAGE	$I_E = -0.4\text{mA}, I_C = -10\text{mA}$	—	—	—	—	—	—	—	—	μA
		$I_E = -1\text{mA}, I_C = -24\text{mA}$	—	—	—	—	—	—	—	—	μA
CE(sat)	COLLECTOR-EMITTER SATURATION VOLTAGE	$I_E = -0.4\text{mA}, I_C = -10\text{mA}$	—	—	—	—	—	—	—	—	μA
		$I_E = -1\text{mA}, I_C = -24\text{mA}$	—	—	—	—	—	—	—	—	μA
PT	PUNCH-THROUGH VOLTAGE I	$V_{EB} = -1\text{V}$	—	—	—	—	—	—	—	—	μA
EQ1	EMITTER-BASE FLOATING POTENTIAL	$V_{CB} = -80\text{V}$	—	—	—	—	—	—	—	—	μA
F ₀	AC COMMON-EMITTER FORWARD CURRENT TRANSFER RATIO	$V_{CE} = -6\text{V}, I_C = 1\text{mA}$ $f = 1\text{K}$	—	—	—	—	—	—	—	—	μA
F ₀	AC COMMON-EMITTER INPUT IMPEDANCE	$V_{CE} = -6\text{V}, I_C = 1\text{mA}$ $f = 1\text{K}$	—	—	—	—	—	—	—	—	μA
F ₀	AC COMMON-EMITTER OUTPUT ADMITTANCE	$V_{CE} = -6\text{V}, I_C = 1\text{mA}$ $f = 1\text{K}$	—	—	—	—	—	—	—	—	μA
F ₀	AC COMMON-EMITTER REVERSE VOLTAGE TRANSFER RATIO	$V_{CB} = -8\text{V}, I_C = 1\text{mA}$ $f = 1\text{K}$	—	—	—	—	—	—	—	—	μA
F ₀	COMMON-BASE OUTPUT CAPACITANCE	$V_{CB} = -8\text{V}, I_E = 0$ $f = 1\text{K}$	—	—	—	—	—	—	—	—	μA
		$V_{CB} = -8\text{V}, I_E = 1\text{mA}$ $f = 1\text{K}$	—	—	—	—	—	—	—	—	μA
F ₀	COMMON-BASE ALPHA CUTOFF FREQUENCY	$V_{CB} = -8\text{V}, I_E = 1\text{mA}$	—	—	—	—	—	—	—	—	μA

p_1 IS DETERMINED BY MEASURING THE EMITTER-BASE FLOATING POTENTIAL V_{EB1} USING A VOLTMETER WITH 11 MEGOHM MINIMUM INPUT IMPEDANCE. THE COLLECTOR-BASE VOLTAGE, V_{CB} IS INCREASED UNTIL $V_{EB1} = -1\text{V}$; THIS VALUE OF $V_{CB} = (V_{EB1} + 1)$ CARE MUST BE TAKEN NOT TO EXCEED MAXIMUM COLLECTOR-BASE VOLTAGE SPECIFIED UNDER MAXIMUM RATINGS.

BASE-EMITTER VOLTAGE
VS
COLLECTOR CURRENT



BASE-EMITTER VOLTAGE
VS
FREE-AIR TEMPERATURE



reverse bias voltage between the collector with the emitter open at which there is a increase in current flow between the collector and base. This point is known as the avalanche breakdown, in which minority electrons, passing through the PN junction, gain sufficient energy to knock valence electrons bound to the crystal lattice and raise them to the conduction band. BV_{CBO} is usually specified at some value of reverse current. The 2N404 will avalanche between collector and base at approximately 25 volts at 20 μ amps of leakage current.

- (4) Emitter breakdown voltage BV_{EBO} is the maximum voltage which can be safely applied between emitter and base when these elements are reverse biased with the collector open. This value is given in specification sheets in order to indicate the maximum reverse bias voltage may be applied to the emitter of a common-emitter amplifier before the emitter-base circuit will break down.
- (5) Many manufacturers will list a collector saturation voltage $V_{CE(sat)}$. This voltage is essentially the minimum voltage necessary, at a particular collector current, to sustain normal transistor action, and it occurs when the emitter-base voltage equals the emitter-collector voltage. At higher collector voltages, the base-collector junction becomes forward biased and the current-voltage relationship changes abruptly. The current increases at a rapid rate limited only by an external resistance in the collector circuit.
- (6) The collector cutoff current is the current from collector to base when no emitter current is applied. This is I_{CBO} . It varies with temperature changes and must be taken into account when the semiconductor is designed into equipment which will be used over a wide range of ambient temperatures.
- (7) Base to emitter voltage V_{BE} is the voltage recommended by the manufacturer for normal transistor action. Notice for the 2N404 V_{BE} is listed for typical and maximum conditions.

1
There are many characteristics of a transistor made to us by the manufacturer. We have discussed only a few characteristics but, as stated earlier, in future you will become familiar with several more important characteristics.

Of the two most important characteristics we have discussed were the maximum reverse bias between collector and base (BV_{CBO}), and the power dissipation rating.

The power dissipation rating of the 2N404 (150 mW) was only another way of expressing the safe amount of heat the collector-base junction can withstand.

In other words, the transistor must dissipate power in the form of heat across the junction. If the power is too high, there will be more than 85°C of heat generated at the junction, which would destroy the device. It was found that we must derate (reduce the output power) the transistor for each degree of increase in ambient temperature as the collector-base junction must dissipate as much heat as it receives from the ambient air.

To assist transistors in achieving higher collector-power dissipation ratings, heat sinks, in which the transistors are mounted, have been developed. These heat sinks, or heat dissipaters, help conduct heat away from the junction, thus lowering the junction temperature (T_j).

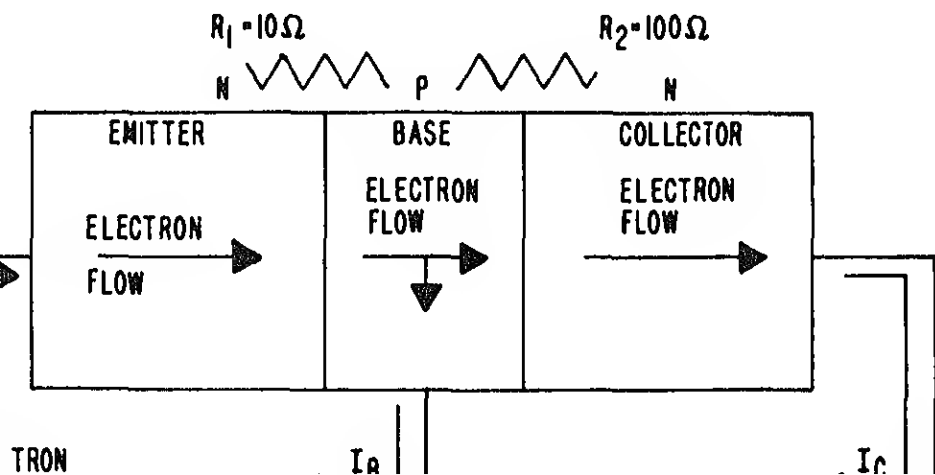
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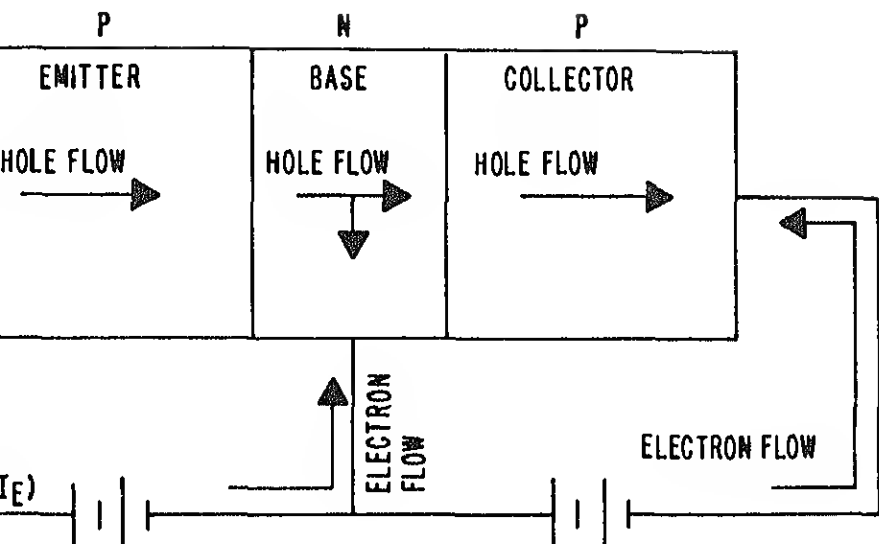
UTLINE:

sistor action



A. Analysis of the NPN Transistor

Analysis of the PNP Transistor

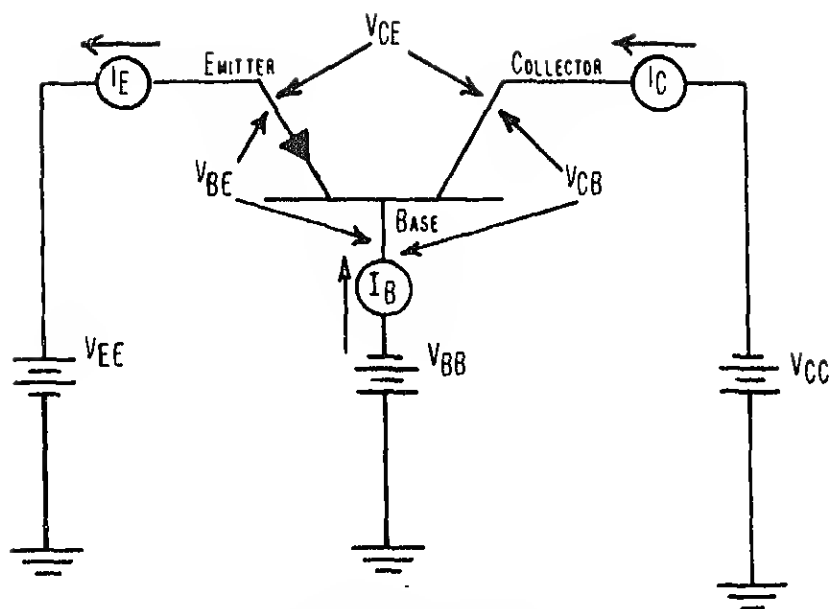


2.6 Figure 2 - PNP Transistor

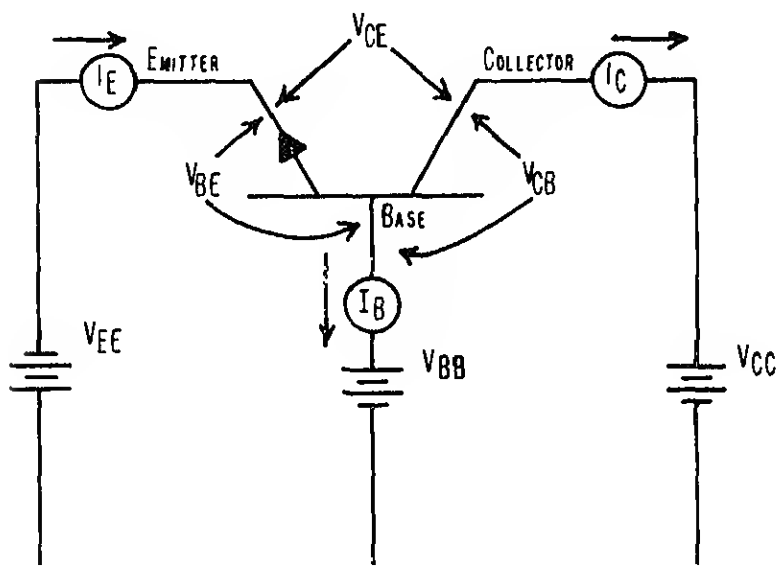
C. Mechanisms of transistor action

II. Transistor symbology and notations

A. Schematic symbols



A. PNP Transistor



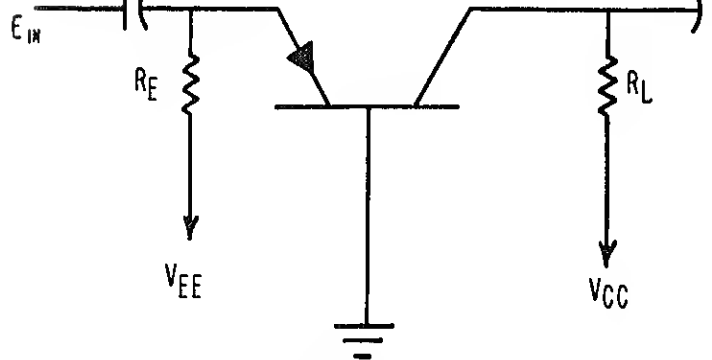
2. PNP type

3. Supply voltages

4. Terminal voltages

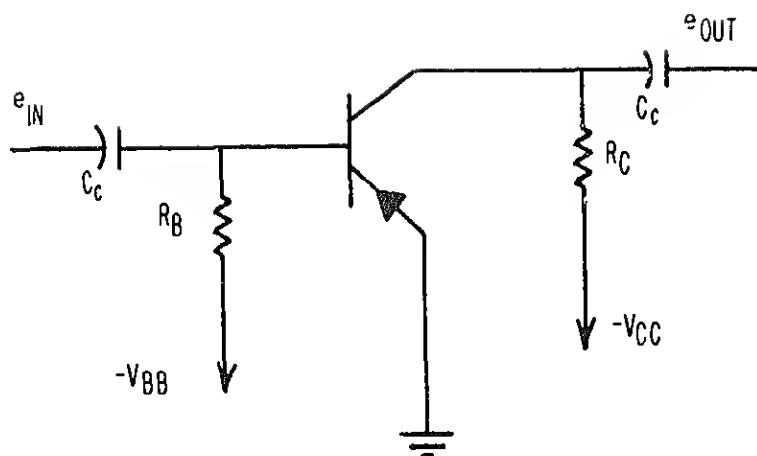
it configurations and operation

three basic configurations



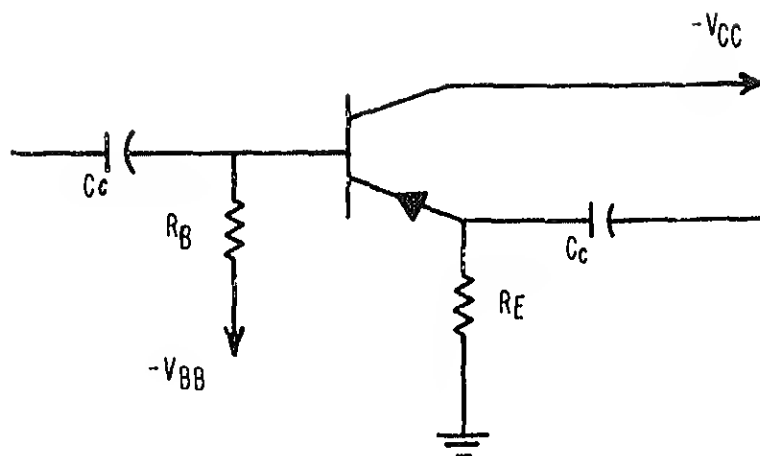
2.7 Figure 4 - Common-Base Amplifier (PNP)

non-emitter amplifier



2.6 Figure 5 - Common-Emitter Amplifier (PNP)

Collector amplifier

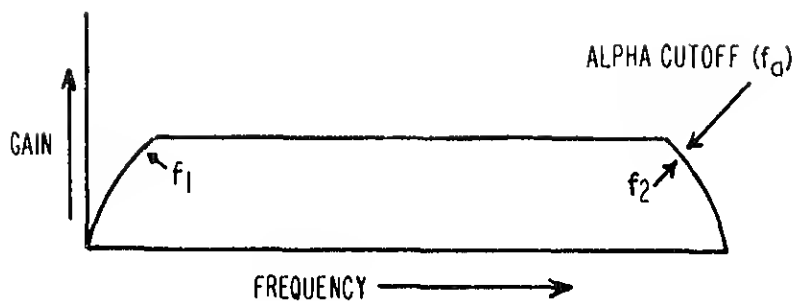


B. Junction temperature

decreased current gain at high levels of transistor current.

noise

E. Frequency response



2.6 Figure 7 - Transistor Frequency Response Curve

this data sheet is for you to measure, record, and
gains and resistances of the three basic transistor
amplifier

amplifier

Draw the following schematic of the common-base ampli-
fied and label components; i.e., V_{CC} , V_{EE} , R_E , R_L , etc.

Measurements and calculations:

$I_C =$ _____

(5) $I_C =$ _____

$R_{CB} =$ _____

(6) $R_I =$ _____

$\beta =$ _____

(7) $A_I(\alpha) =$ _____

$R_{CB} =$ _____

Measurements

$V_{out} =$ _____

$V_{in} =$ _____

$V =$ _____

Equations:

Write the formula for V_{EB} for the above schematic.

2. Common-collector amplifier

- a. Complete the following schematic of the common-c amplifier and label components.

- b. Static measurements and calculations:

(1) $V_B =$ _____

(6) $V_{BE} =$ _____

(2) $V_C =$ _____

(7) $I_E =$ _____

(3) $V_E =$ _____

(8) $R_I =$ _____

(4) $I_B =$ _____

(9) $A_I(\gamma) =$ _____

(5) $V_{BC} =$ _____

- c. Dynamic measurements:

$=$ _____

$=$ _____

$=$

What are the bias voltages correct for normal transistor operation?

What is the voltage gain characteristic of the common-collector amplifier? _____

Instructor's initials _____

Common-emitter amplifier

Draw the following schematic of the common-emitter amplifier and label components.

(4) $I_B =$ _____

(9) Λ

(5) $V_{BE} =$ _____

c. Dynamic measurements:

(1) $e_{out} =$ _____

(2) $e_{in} =$ _____

(3) $\Lambda_V =$ _____

d. Questions

(1) What would happen to forward bias if

(2) Are the bias voltages correct for no operation?

Instructor's

istor means setting the d-c voltages and currents of to certain chosen values to establish an operating a-c signal. A bias circuit employs resistors and d-c to set the various voltages and currents at the pre-es. These d-c voltages and currents must be such he transistor's ratings are exceeded; that is, they the permissible operating point region.

Circuit Analysis, NAVAIR 00-80-T-79, Chapter 8.

Kiver, Transistor and Integrated Electronics.
N. Y., McGraw-Hill Book Company, 1972, Fourth

on

he a-c signal is applied to the transistor, the stor's voltages and currents vary about the operating Only a portion of the permissible operating point is such that the amplification is linear; this n of the permissible operating point region is called near operating region. The entire signal swing must n in the linear operating region for the input to be ed without appreciable distortion.

are two major reasons for the difficulty in sustain-desired operating point. First, as was noted in duction to Semiconductors," the characteristics of nductor materials are temperature dependent. Second, aracteristics of different transistors of the same ll vary from unit to unit. Consequently, when s transistors are placed in the same circuit, the ion will vary somewhat unless stabilizing measures ken.

transistor and the means for removing heat from the transistor. Changes in temperature affect three transistor quantities: I_{CBO} , β , and V_{EB} . β and I_{CBO} will rise as the temperature increases. The V_{EB} which is necessary to produce a given emitter current decreases as the temperature increases. Of these, the most serious variation is experienced by

1. Reverse-Bias Collector Current (I_{CBO}). I_{CBO} (sometimes referred to as I_{CO}) is normally measured at a T_j (junction temperature) of 25°C (see figure 1). Note that I_{CBO} is a minority current, and flows in the same direction as the collector current if the transistor was properly biased. This current I_{CBO}/I_{CO} is the same type current as I_{CO} that flows in any PN junction under a reversed bias condition (see figure 2). The current flow in the reverse-biased condition is almost constant and independent of the applied voltage prior to the breakdown point.

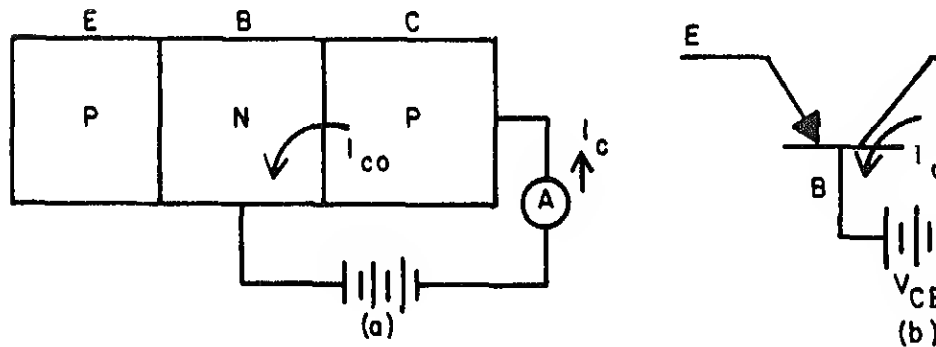
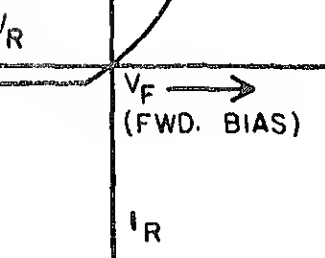
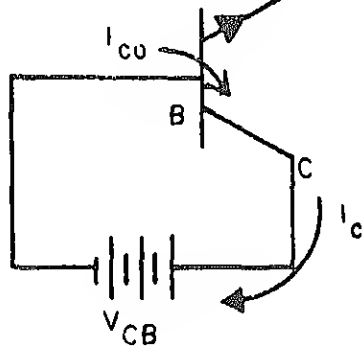


Figure 1

- a. Variations of I_{CBO}/I_{CO} with temperature of the collector-base junction is shown in figure 3. The current value varies from almost zero at 10°C to well over 1 milliamperes at 125°C . Note that at temperatures below 10°C , I_{CBO} causes no problem. I_{CO} doubles for every 10°C rise in germanium and every 6°C rise in silicon.



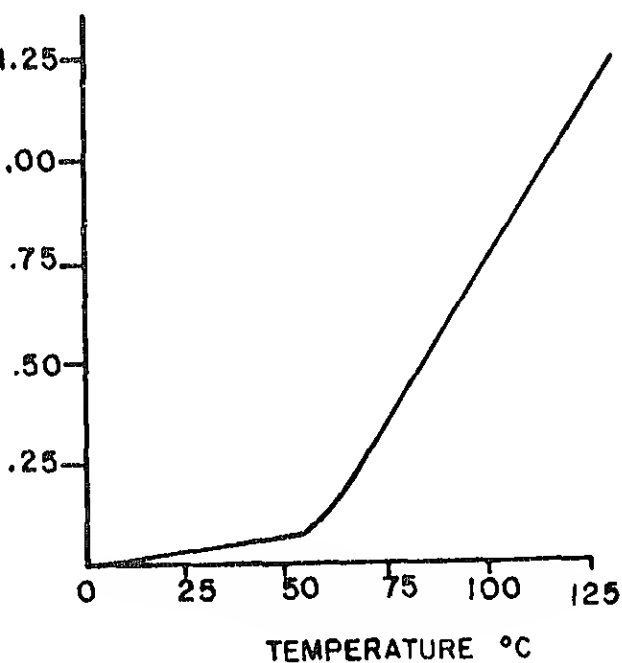
(a)



(b)

PN Junction Characteristics

Figure 2



base are high in value, electrons from the collector can accumulate in the base region. Such an accumulation of electrons will cause an increase of emitter hole into the base, increasing collector current. Increased collector current would raise the temperature of the collector-base junction, and cause an increase in I_{CO} (figure 3). The cycle would continue until severe distortion occurs, the transistor becomes inoperative, or it destroys itself. THIS CONDITION BE MINIMIZED BY AVOIDING THE USE OF HIGH-VALUED RESISTORS IN THE BASE LEAD.

Beta - β is the current gain of the common-emitter transistor configuration. It is the ratio of a change in collector current (ΔI_C) caused by a change in base current (ΔI_B). I_{CBO} flows through the base lead in opposite direction to I_B (figure 4), increases I_{CBO} , causes I_C to increase, and I_B to decrease. Therefore, for a set value of I_B β would increase and shift the operating point.

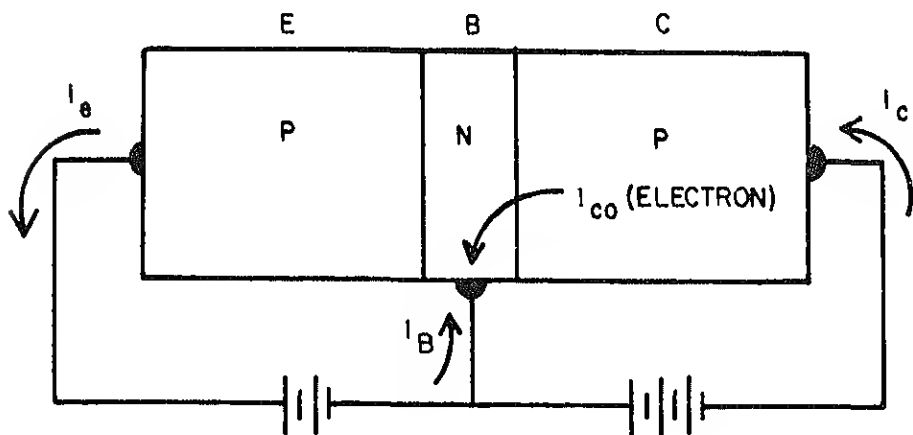
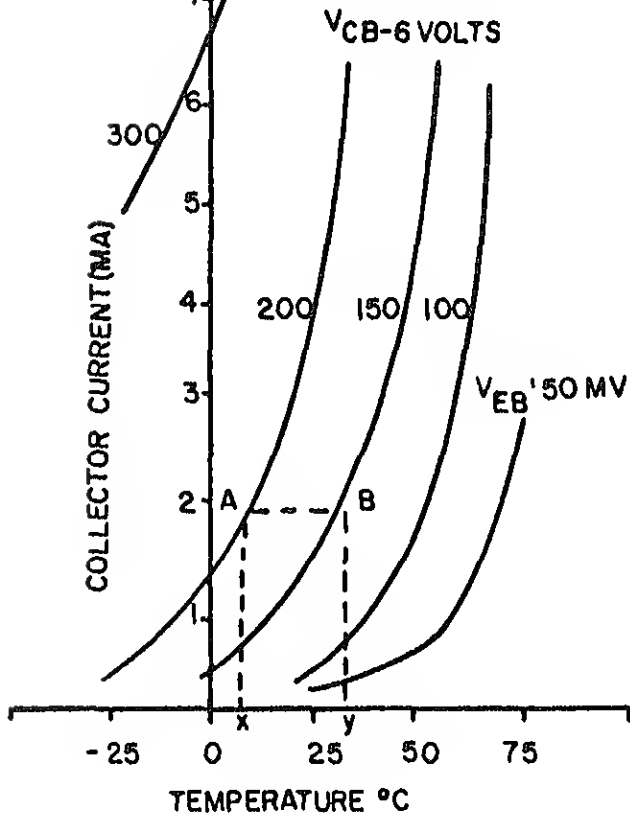


Figure 4

V_{EB} - Figure 5 indicates the variation of collector current with temperature. Each curve is plotted with a fixed collector-base voltage (V_{CB}) and a fixed emitter-base



variation of Collector Current with Transistor Temperature

Figure 5

Method of reducing the effect of the NEGATIVE TEMPERATURE COEFFICIENT of resistance is to place a value resistor in the emitter lead. Essentially, it causes the variation of emitter-base junction resistance to be a small percentage of the total resistance in the emitter circuit. The external resistor (overcomes) the junction resistance; the resistor is referred to as a swamping resistor.

Second method of reducing the effect of the temperature coefficient of resistance is to use emitter-base forward bias as the temperature

$$\frac{\text{Difference in forward bias}}{\text{Difference in temperature}} = \frac{50 \text{ mV}}{20^\circ\text{C}} = 2.5$$

This calculation indicates that collector current will not vary with emitter-base junction resistance. If forward bias is reduced $2.5 \text{ mV}/^\circ\text{C}$ for increased temperature, or increased $2.5 \text{ mV}/^\circ\text{C}$ for decreased temperature.

Common-Emitter Amplifier

1. The common-emitter amplifier is the most commonly used amplifier because it has the following characteristics:
 - a. Current gain; $\beta = \frac{\alpha}{1-\alpha}$
 - b. Voltage gain $\approx \beta \approx \frac{R_O}{R_i}$
 - c. Highest power gain
 - d. Easier to cascade because $\frac{R_O}{R_i}$ is more closely

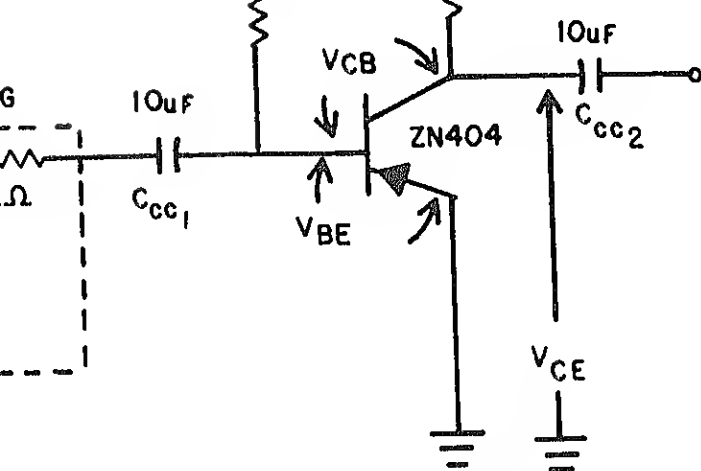
However, it must be stabilized because of unit gain variations, and temperature instability.

- (1) There are several biasing arrangements used for a common-emitter amplifier to compensate for instability. Constant base current biasing is shown in figure 6 and will be used to analyze basic biasing.

$$I_B = \frac{V_{CC} - V_{BE}}{R_B} = \frac{5.8\text{V}}{1\text{M}} = 5.8 \text{ } \mu\text{A}$$

$V_{BE} \approx .2\text{V}$ for germanium; since $R_B \gg$ the diode resistance, I_B will be limited primarily by R_B .

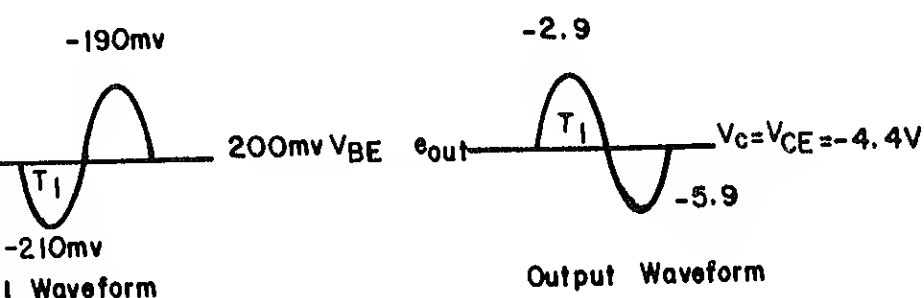
$$I_C = \beta I_B = 100 \times 5.8 \text{ } \mu\text{A}$$



constant-base-current bias common-emitter amplifier

Figure 6

re, the collector voltage $V_C = V_{CE}$ is 4.4 volts. The output waveform will vary around this point (4.4) as shown in figure 7.



$$= \frac{3.0V}{20mV} = 150$$

Eq (1.5)

output waveform versus input waveform

parameter I_{CBO} was not included. I_{CBO} current that flows collector to base with emitter open. However, transistor action occurs with the emitter open. If, on the other hand, I_{CBO} flowed only in the collector-base junction, it would cause no serious problem. But, if the transistor is constructed that has a high resistance base lead, it will appear open to this current. This will cause a current to flow I_{CEO}^* (figure 8). These minority carriers recombine in the base.

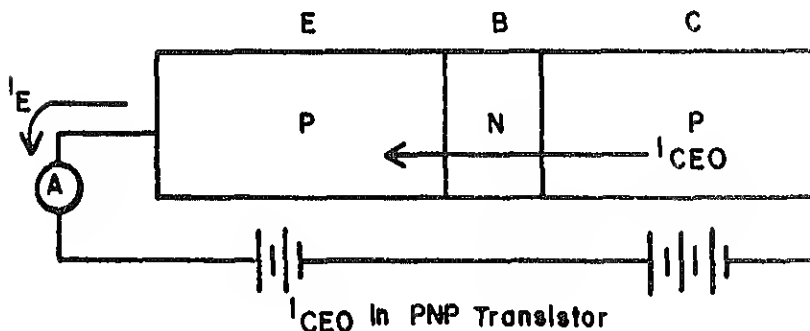


Figure 8

circuits and become majority carriers. At the emitter, this is the same as an increase in bias current. The emitter injects $\beta + 1$ times the base current to offset the negative charge on the base. β holes will diffuse through the base and recombine with I_{CO} .

Mathematically:

$$I_{CEO} = I_{CBO} (B+1) = I_{CO} (B+1)$$

The collector current (I_C) is:

$$I_C = \beta I_B \text{ (Eq 1.2) } + I_{CEO}$$

$$= \beta I_B + I_{CEO}$$

$$= \beta I_B + I_{CO} (B+1)$$

$$(100)(5.8 \mu A) + 5 \mu A (101)$$

$$(1.085 \text{ mA})$$

$$V_{CC} - I_C R_L = 6 - (1.085 \text{ mA})(2.76 \text{ k}\Omega) \quad (\text{Eq 1.8})$$

$$6 - 2.99 \approx 3 \text{ volts}$$

ual operating point would be $V_{CE}=3$ volts and the output signal would be symmetrical if the remained 20 mV p-p and A_V 150. However, if the temperature increases and cause I_{CO} to increase, I_C will increase. This would create more heat and more I_{CO} . This process is called thermal runaway and could damage the transistor if R_L is very small. In our example, if the temperature increased and caused I_{CO} to increase to a small current compared to I_C , the new operating point will be:

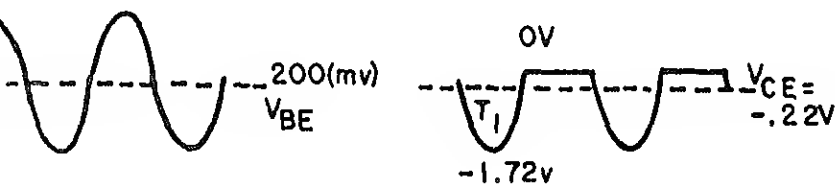
$$V_{CC} - I_C R_L \quad (\text{Eq 1.9})$$

$$V_{CC} - \{100 \times 5.8 \mu A + (15 \mu A)(101)\}(2.76 \text{ k}\Omega)$$

$$6 - 5.78$$

$$= .22 \text{V (saturation)}$$

Input signal and A_V remained the same, then:



Input Waveform

(b) Output Waveform

Figure 9

It indicates the change in collector current change in I_{CBO} . The optimum value of S equals 1, then I_C will change only by the I_{CBO} . This is an idealized objective and realizable with ordinary measures. The v is always greater than 1 for the common-emitter. However, it should be remembered that the value of S is to 1, the better.

Apply equation 1.10 to figure 6.

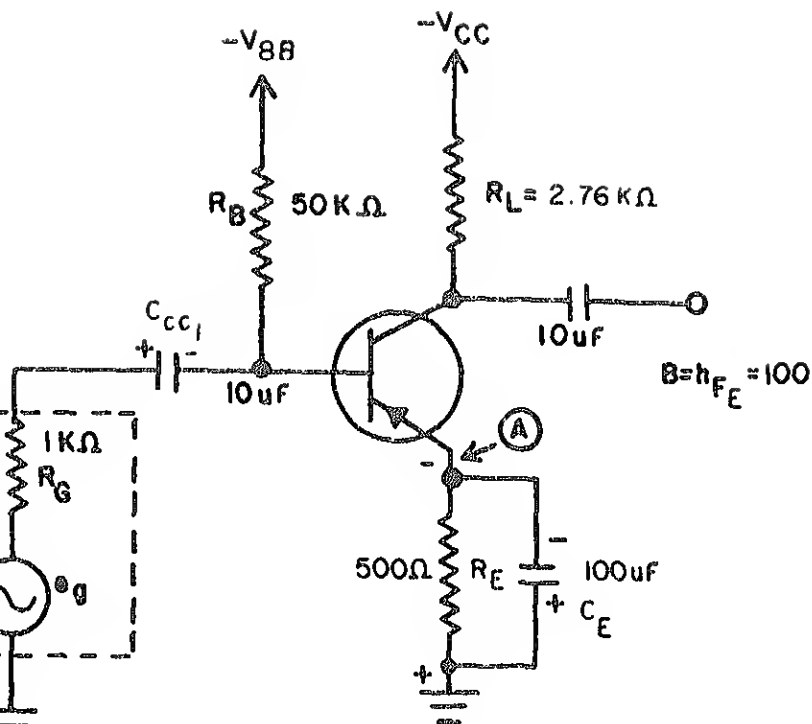
$$S = \frac{\Delta I_C}{\Delta I_{CBO}} = \frac{\Delta I_{CEO}}{\Delta I_{CBO}} = \frac{1,010 \mu A}{10 \mu A} = 101$$

The stability factor of the unstabilized amplifier (figure 6) approximately equals current gain. We will see in the following how this value is improved by various stabilization schemes.

- b. Figure 10 is a bias scheme used to improve of the circuit. The addition of an emitter (swamping resistor) increases the stability of the circuit by:

- (1) Compensating for the negative coefficient of the emitter base junction.
- (2) Unit to unit variations, since this is the same as temperature variations.
- (3) Providing a constant current source.

The resistor R_E adds the disadvantage of since it develops a voltage that is degenerative to the input signal. If greater gain is required, it can be passed with a capacitor. R_E is reduced to zero in the bias scheme is called constant emitter current since it attempts to maintain I_E constant. A variation in I_E would cause a more negative voltage developed at point (A) in figure 10, which would reduce bias and reduce transistor current. A variation in I_E would increase the voltage at point (A), which would increase the bias and increase the transistor current.



r Current Biased Common Emitter Amplifier

Figure 10

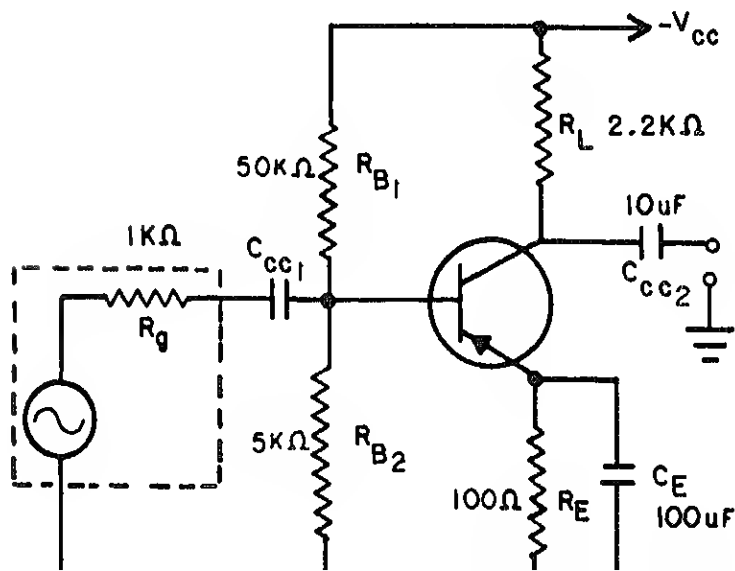
the circuit. Under dynamic conditions, the s at a-c ground due to the bypassing action of should be remembered that bias stability deals conditions and C_E simply keeps the emitter at d. Through the use of calculus it can be t the stability factor for the circuit in is

$$\begin{aligned} \frac{\Delta I_C}{I_{CBO}} &= \frac{(R_B + R_E)(\beta + 1)}{R_B + (1 + \beta)R_E} & (\text{Eq 1.11}) \\ &= \frac{(50 \times 10^3 + .5 \times 10^3)(101)}{50 \times 10^3 + (.5 \times 10^3)(101)} \end{aligned}$$

$$= 5100.5 \times 10^3$$

zero, the stability factor approaches ideal. Further, if R_E approaches zero the stability factor approaches $\beta + 1$. Therefore, for good stability R_B should be small as possible and R_E as large as possible. One cannot make R_E larger and R_B smaller indefinitely, however, even though R_E can be a-c bypassed by a capacitor, the power supply voltage must be made larger as R_E is increased. For R_B , a lower limit is set by the shunt effect on the a-c signal if the stage is capacitively direct coupled; if it is transformer coupled, the limit on R_B is set only by the magnitude of the base voltage.

- d. The stability, it is noted, is affected by R_E , R_B , and Beta of the transistor. Note also, that the stability does not depend on R_L . The stability factor used in this circuit will depend on whether the I_C variation is permissible, in terms of signal swing, permissible power dissipation, or the conditions for thermal runaway. If not, then R_E must be raised or R_B lowered until a suitable condition is found.
- e. The most frequently used biasing circuit is shown in figure 11 where an additional resistor is added to the base circuit.



$$\text{Beta}$$

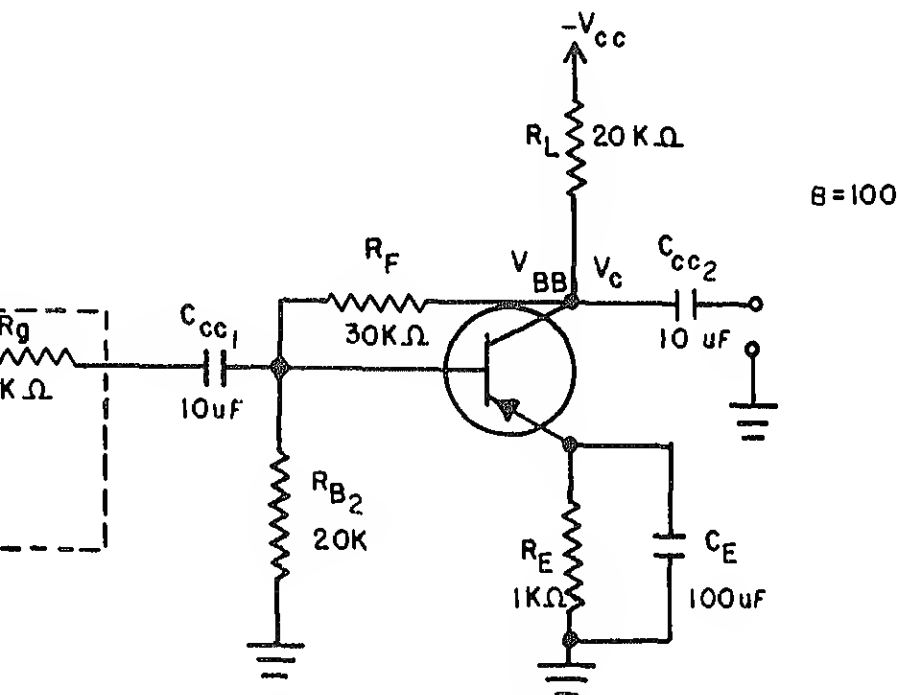
$$S = \frac{(R_B + R_E)}{R_B + (1/\beta) R_E}$$

$$R_B = \frac{(R_B + R_E)}{\beta}$$

...large to establish the proper forward bias. This would decrease the stability of the circuit.

res 10 and 11, the swamping resistor develops negative d-c current feedback. If a-c stability is desired, the removal of the emitter bypass capacitor will provide a-c current feedback.

A general method for stabilizing the operating point consists of using direct voltage feedback with current feedback (figure 12).

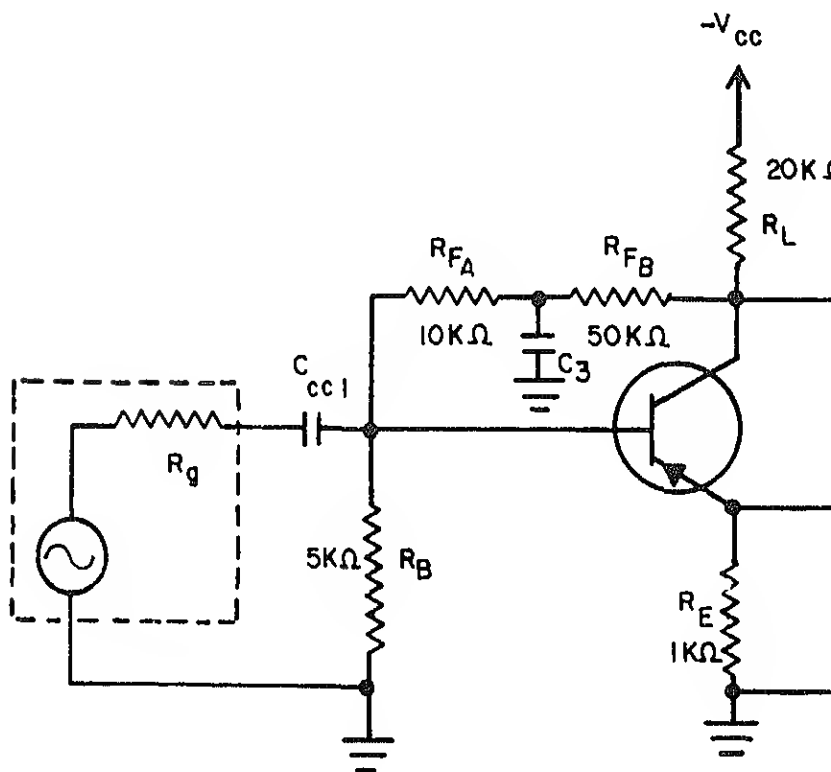


Instant-Collector-Voltage Biased
Common-Emitter Amplifier

Figure 12

Feedback is defined as that situation when the output of signal fed back to the input (from the output) upon a voltage in the output circuit.

If greater gain is required, the circuit can be modified as in figure 13. The capacitor C_3 bypasses the feedback generation without altering the d-c circuit because $R_{FB} \parallel R_L$ and reduces the a-c load



Constant-Collector-Biased Common-Emitter Amp

Figure 13

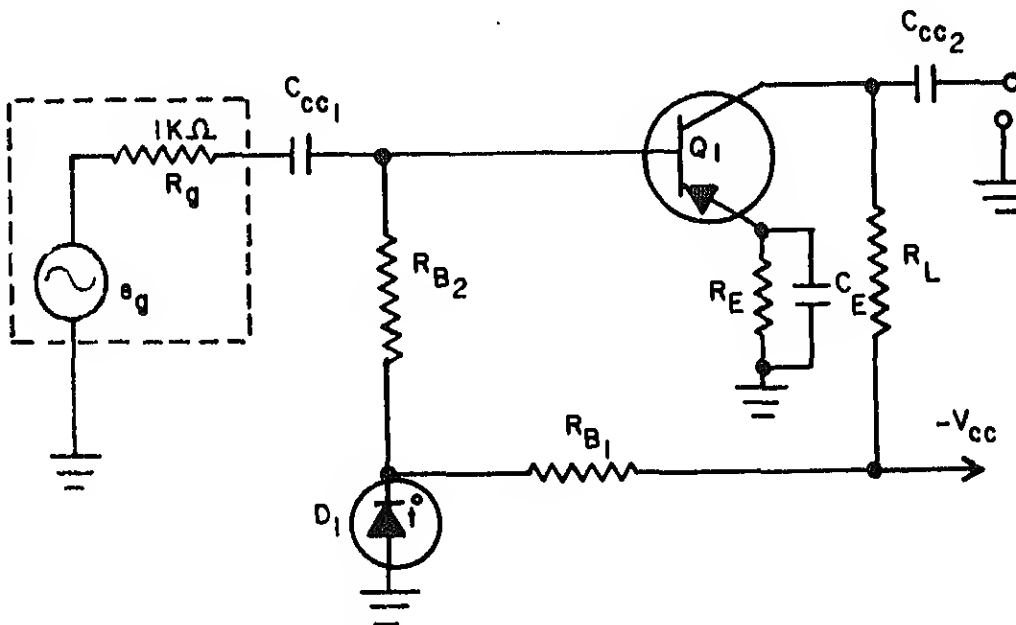
- i. These, are the stabilizing schemes and eq on the common emitter. The choice between current-feedback is largely determined by the d-c load resistance. If the d-c R_L is usually the case for RC-coupled amplifier feedback (emitter at a-c and d-c ground) as the current type. For transformer coupled the d-c R_L is low, current feedback is mu

- (1) Determine the appropriate S value and then use various d-c equations to fix the circuit component values which will give the S .
- (2) Decide upon the component values by the usual considerations and then check the resulting S .

Additional Stabilizing Techniques

When using temperature-sensitive elements for stabilization, the idea is to cause the circuit conditions to change with temperature so that the changes effected by the transistor are compensated.

Figure 14 is an example using a diode (D_1) that has similar characteristics as the emitter-base junction of Q_1 (negative temperature coefficient). Any temperature variation will affect the base voltage and correct I_B to compensate for the change. Note also that current feedback is still used.



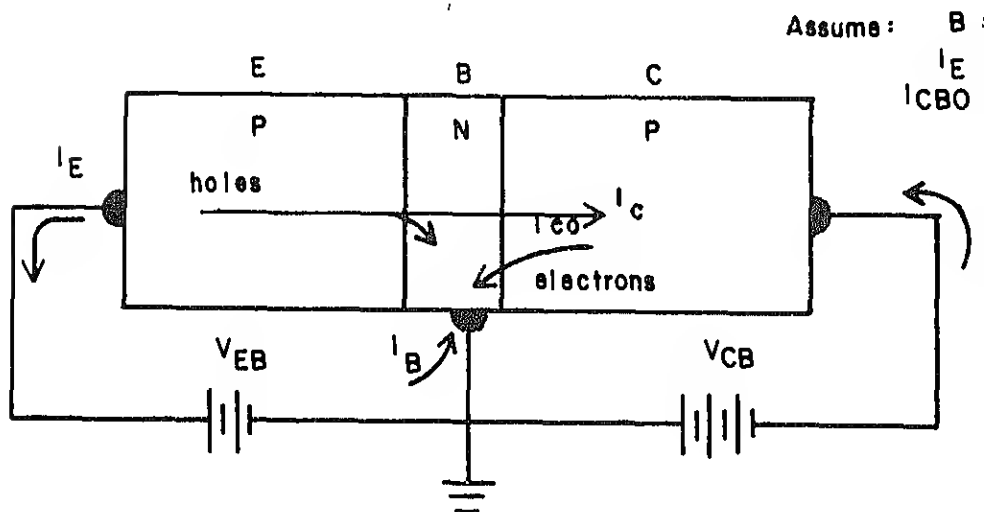
Temperature-Compensated Common-Emitter Amplifier

- a. Capable of the highest voltage gain of the three configurations;

$$A_V \approx \alpha \left(\frac{R_O}{R_i} \right)$$

- b. A current gain called Alpha = $\frac{\Delta I_C}{\Delta I_E}$ always less than one.
- c. Very low input resistance; high output resistance.
- d. Used mainly where the matching of a low to a high resistance is required.
- e. Ideal stability factor in the basic circuit configuration.

2. Figure 15 will be used to illustrate the common-base amplifier, its current flow and direction of current



Current Flow in a PNP Transistor

Figure 15

I_C

- 4.95mA

Collector current did not include the effect of

$$\alpha I_E + I_{CO}$$

$$(.99)(5,000 \mu A) + 25 \mu A = 4,975 \mu A$$

$$- \alpha) - I_{CO}$$

$$\mu A (1 - .99) - 25 \mu A$$

$$- 25 \mu A$$

clear that if I_{CO} decreases I_B by its increase;
constant and I_C will change only by I_{CO} .
an ideal stability factor.

or using constant emitter current biasing is
figure 16.

$$- I_E R_E = 6 - \{1mA \times 5.8k\} = + .2V \quad (Eq 1.13)$$

$$I_C R_L = V_{CC} - (\alpha I_E + I_{CO})(R_L) \quad (Eq 1.14)$$

$$\{(.99)(1000 \mu A) + 5 \mu A\} \{3.1k\}$$

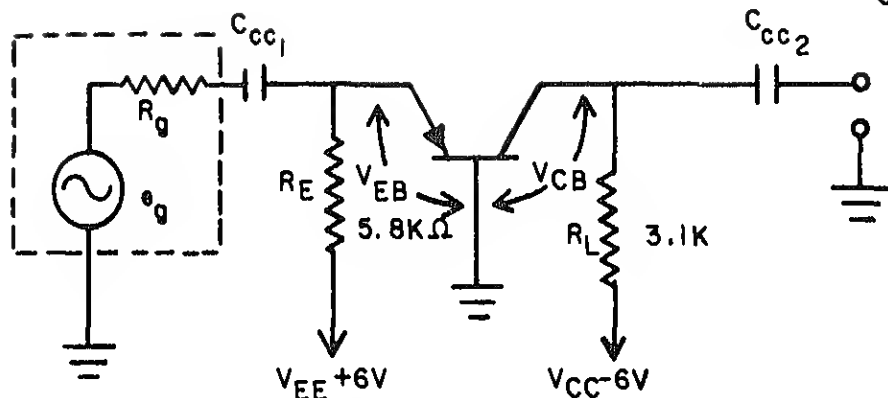
ts

$$V_B \quad (Eq 1.15)$$

-(0)

olts

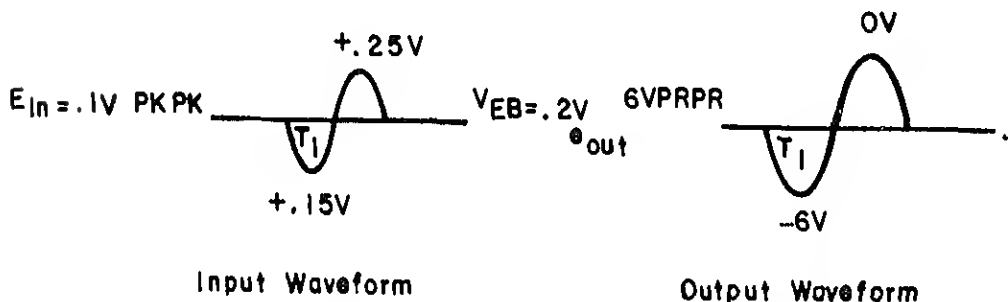
Assume: I_E
0
 I_{CO}



Constant Emitter Current Biased Common Base Amplifier

Figure 16

With the bias voltages computed, the amplifier is properly biased. Assuming a voltage gain of 60 and input signal of .1 volts p-p, the output signal is given in figure 1. The operating point is 3 volts (V_{CB}) and the maximum output without distortion is used.



$$\Delta I_{CBO} R_B + (\beta + 1) R_E$$

$$S = \frac{R_E(\beta + 1)}{R_E(\beta + 1)} = 1; \text{ ideal stability}$$

change in I_{CQ} will change I_C by the same amount. current that becomes I_{CEO} simply aids the circuit in stability. A disadvantage of this circuit is that requires two power supplies. One power supply could be used with a voltage divider network; however, one must remember any resistance added in the base increases the stability factor.

Emitter Amplifier

Common-collector amplifier has the following characteristics:

highest current gain; $\gamma = \beta + 1$

voltage gain less than one; $A_V = \gamma \left(\frac{R_O}{R_i} \right)$

high input resistance; low output resistance.

used mostly for impedance matching.

provides a-c and d-c stability due to its degenerative feedback.

The common-collector amplifier is shown in figure 18.

The voltages are as follows:

$$V_{BB} = I_B R_B + I_E R_E \quad (\text{Eq 1.16})$$

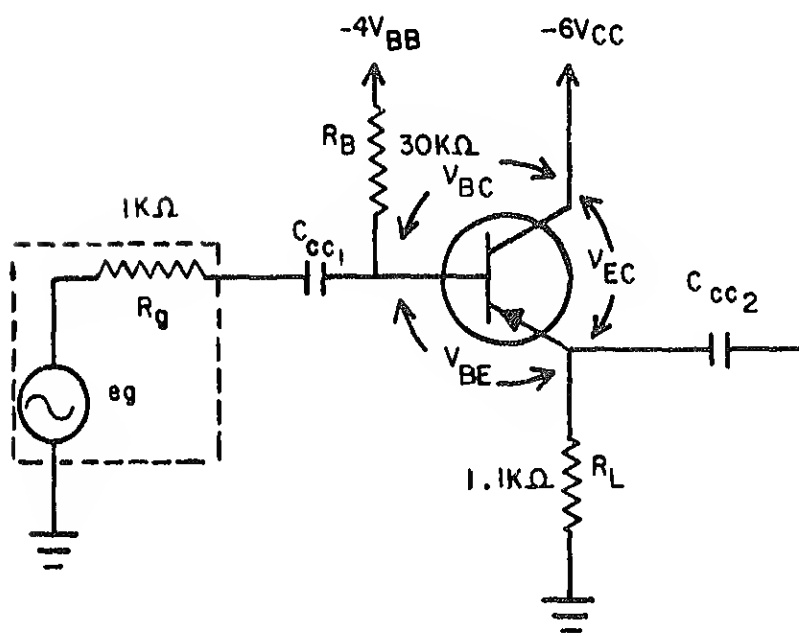
$$4 = \{(27 \times 10^{-6})(30 \times 10^3)\} + \{(101)(27 \times 10^{-6})(1.1 \times 10^3)\}$$

0.19 volt

$$V_E = V_{CC} - I_E R_E \quad (\text{Eq 1.17})$$

$$\begin{aligned}
 &= -6 - \{4 - (-.8)\} \\
 &= -6 - (-3.2) \\
 &= -2.8 \text{ volts}
 \end{aligned}$$

As

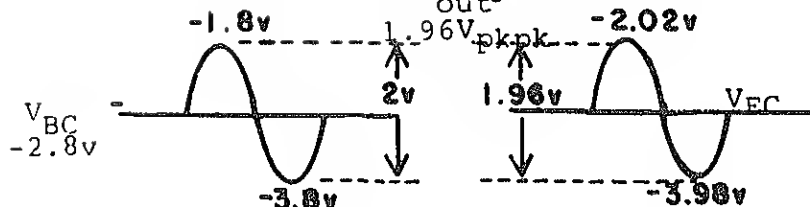


Basic Common-Collector Amplifier

Figure 18

If a 2V p_p signal was applied to the amplifier, the output would be as shown in figure 19.

2. The S of this circuit is approximately equal to R_B to R_L . Equation 1.9 could be used to analyze the circuit also. The common collector amplifier



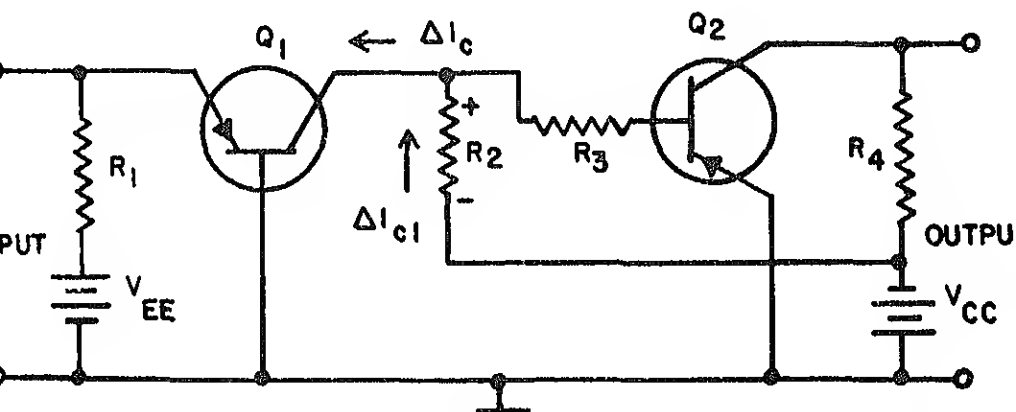
(a) INPUT WAVE FORM

(b) OUTPUT WAVEFORM

Output Waveform Versus Input Waveform
Common-Collector Amplifier

Figure 19

amplifier - Sometimes direct-coupled amplifiers are used to utilize I_C variations. An example is given in figure 20. This amplifier amplifies d-c voltage and very low frequency signals. This circuit is arranged so that an increase in collector current caused by a temperature rise in transistor Q_1 will reduce the forward bias in transistor Q_2 . The voltage across resistor R_2 opposes the forward bias on Q_2 . By selecting the values of resistors R_2 and R_3 so that the voltage across R_2 is the larger, the change in I_C of Q_1 will have a tendency of transistor Q_2 collector current to increase with temperature.



2. Items that should be remembered concerning biasments are:

- a. Reverse-bias collector current I_{CBO} , also increases rapidly at high temperatures and increased collector current.
- b. Emitter-base junction resistance decreases creasing temperature and causes increased current.
- c. The stability factor (S) is defined as the change in collector current (ΔI_C) to a change in minority current (ΔI_{CBO}) and is expressed as

$$S = \frac{\Delta I_C}{\Delta I_{CBO}}$$

- d. An emitter swamping resistor minimizes variation in emitter current caused by variations in emitter-base junction resistance.
- e. Zero base resistance limits the accumulation of minority carriers (I_{C0}) in the base region and therefore the increase in emitter current due to this.
- f. The basic common-base amplifier (figure 16) has the best temperature stability because it uses an emitter swamping resistor and zero base resistance.
- g. The basic common-emitter amplifier (figure 17) has poor temperature stability because it uses an emitter resistor and zero emitter resistance.
- h. The temperature stability of the basic common-emitter amplifier (figure 18) depends upon the ratio of collector resistance to emitter resistance.

Circuit Analysis, Vol. I, NAVAIR 00-80-T-79,

Kiver, Transistor and Integrated Electronics. New
, McGraw-Hill Book Company, 1972, Fourth Edition.

LINE:

1 Information - Biasing

ional Analysis of the Common-Emitter Amplifier
iasing

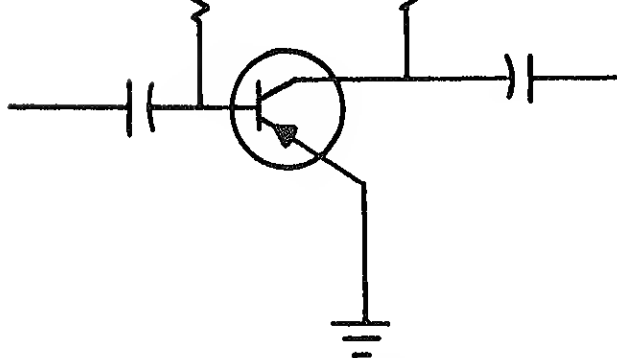


Figure 1

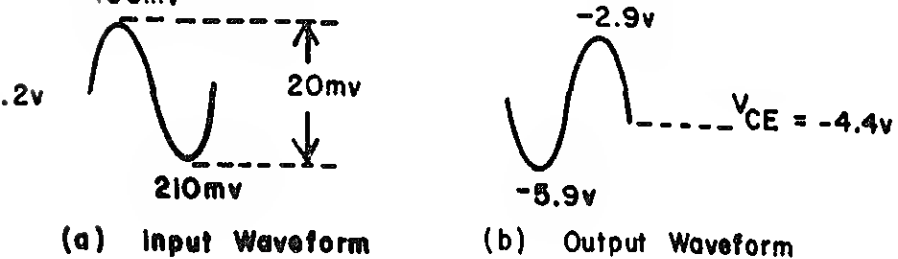


Figure 2

Temperature variations

Reversed bias collector Current (I_{CB0})

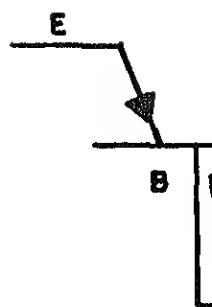
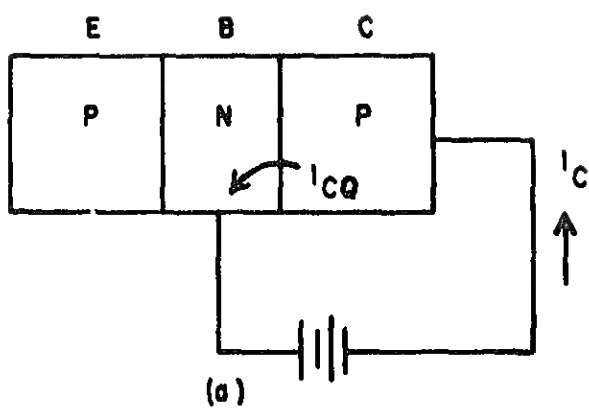


Figure 3

D. Beta

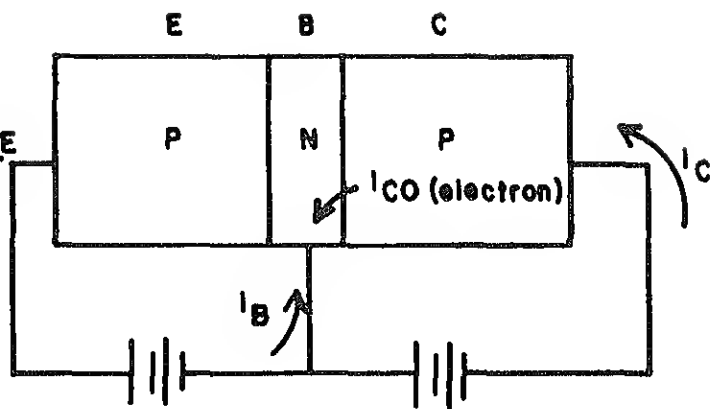
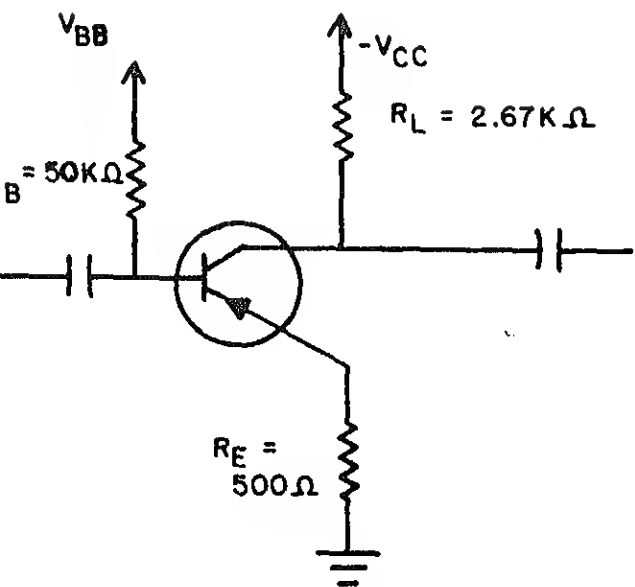


Figure 4

ant-emitter-current biased common-emitter amplifier



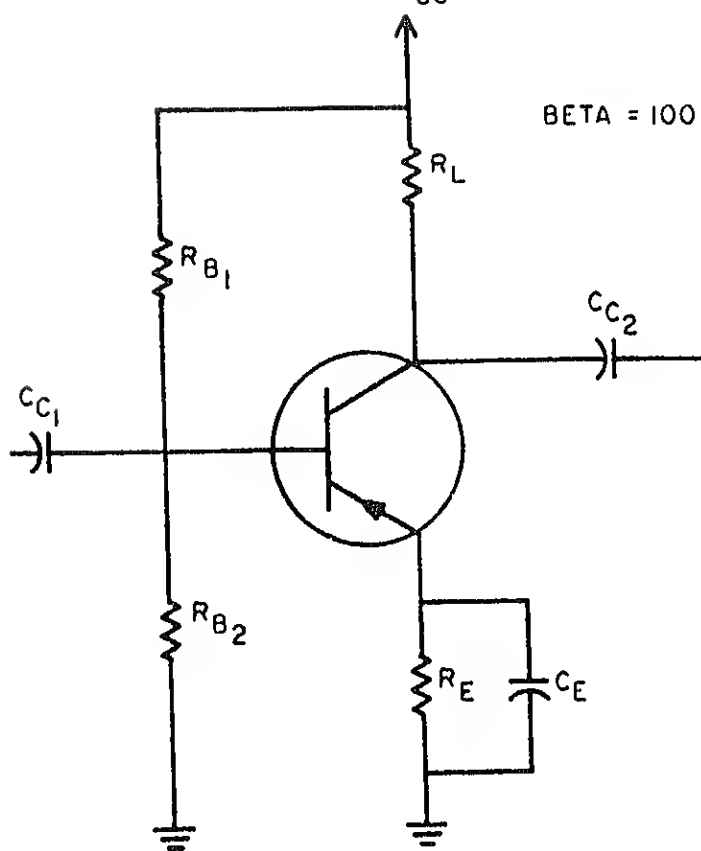


Figure 6

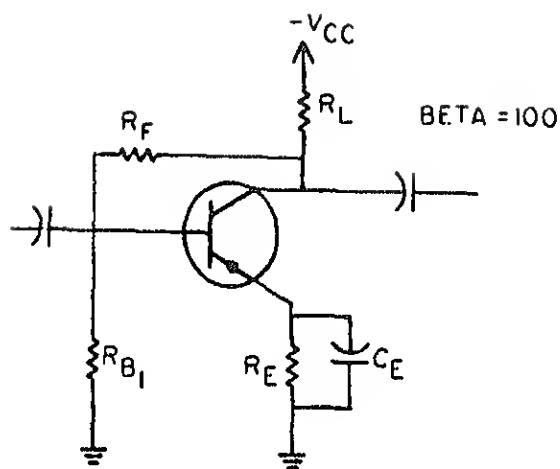
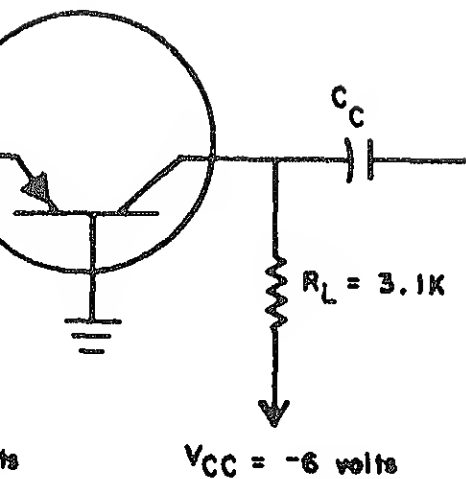
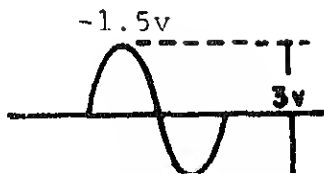
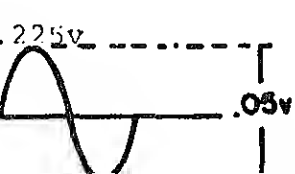


Figure 7



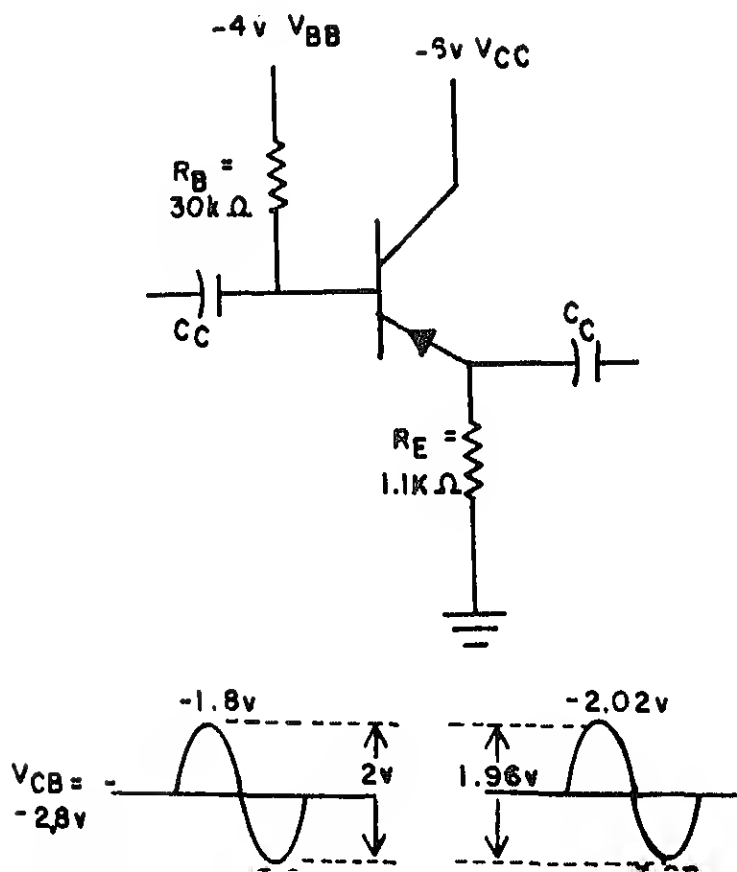
ASSUME: $I_E \approx 1 \text{ mA}$
 $\text{ALPHA} = .99$
 $I_{CO} \approx 5 \mu\text{A}$



$V_{CB} = -3\text{v}$

V. Operational Analysis of the Common-Collector

A. Biasing



the data sheet is for you to record the effects of a transistor's operating point. You will apply heat r , and you will measure and record the resulting current with and without compensating circuit components.

e effects

ishing operating conditions:

= _____

$E =$ _____

$E =$ _____

output waveform

_____ V_{p-p}

$=$ _____

$CE =$ _____

s of increased temperature:

$V_{BE} =$ _____

$\Delta V_{BE} =$ _____

$I_C =$ _____

$\Delta I_C =$ _____

output waveform

_____ V_{p-p}

$CE =$ _____

(2) how is v_{BE} affected by temperature changes?

(3) Does temperature affect fidelity? Explain.

(4) What would be the result of a transistor's
to extreme heat for a prolonged period of t

Instructor's initials

2. Reducing temperature instability with the addition
resistor.

a. R_7 equals $10\text{ k}\Omega$

(1) $I_C =$ _____

(2) I_C after heating = _____

(3) $\Delta I_C =$ _____

b. R_7 equals $100\text{ k}\Omega$

(1) $I_C =$ _____

(2) I_C after heating = _____

(3) $\Delta I_C =$ _____

c. $E_{out} =$ _____

d. $E_{in} =$ _____

e. $A_v =$ _____

ons

Does the introduction of an emitter resistor improve transistor temperature stability? Why?

Does the size of the emitter resistor affect transistor temperature stability? Explain.

What is a disadvantage of using an emitter resistor?

How can the above disadvantage be compensated for?

Does the emitter bypass capacitor stabilize I_{CQ} ? Why?

Instructor's initials _____

Effect of R_B and R_E on temperature stability and A_v .

Power heat = _____

= _____

j. $E_{out} =$ _____

k. $E_{in} =$ _____

l. $A_v =$ _____

m. Questions

- (1) In terms of stability, what conclusion regarding ratio of R_B to R_F can be drawn from this experiment? Explain?

- (2) Why is it desirable to have I_{CO} flow through collector-base junction rather than both the base and the emitter-base junction? Explain.

Instructor's initials _____

4. Constant collector-voltage feedback to improve stability

a. Operation at ambient temperature:

(1) $I_C =$ _____

(2) $E_{out} =$ _____

(3) $E_{in} =$ _____

(4) $A_v =$ _____

(5) I_C with heat applied = _____

h heat applied = _____

constant-base voltage bias to constant-collector
as, explain any difference in their effects on
stability.

Instructor's initials' _____

Adams, Basic Mathematics for Electronics. New York:
McGraw-Hill Book Company, Inc., Third Edition, Chapters 34 and

Electronics, Volume 1. NAVPERS 10087-C. Washington,
United States Government Printing Office, 1979,
pages 221-231.

LINE:

of Logarithms.

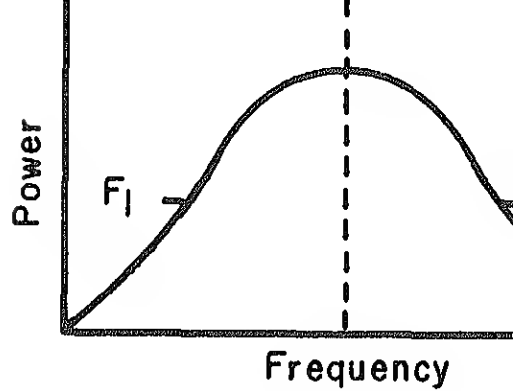


Figure 1 Bandwidth Cur

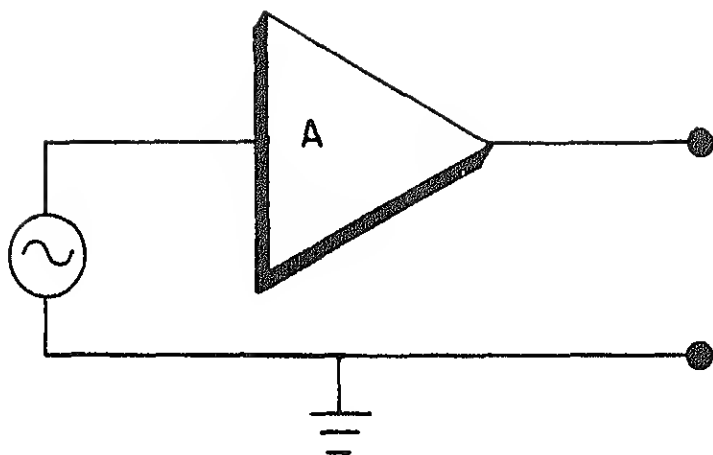
3	4771	4914	5051	5185	5315	5441	5563	5682	5798	5911
4	6021	6128	6232	6335	6435	6532	6628	6721	6812	6902
5	6990	7076	7160	7243	7324	7404	7482	7559	7634	7709
6	7782	7853	7924	7993	8062	8129	8195	8261	8325	8388
7	8451	8513	8573	8633	8692	8751	8808	8865	8921	8976
8	9031	9085	9138	9191	9243	9294	9345	9395	9445	9494
9	9542	9590	9638	9685	9731	9777	9823	9868	9912	9956
10	1000	1043	1086	1128	1170	1212	1253	1294	1334	1374
11	1414	1453	1492	1531	1569	1607	1645	1682	1719	1755
12	1792	1829	1864	1899	1934	1969	2004	2038	2072	2106
13	2135	2173	2206	2239	2271	2303	2335	2367	2399	2430
14	2461	2492	2523	2553	2584	2614	2644	2673	2703	2732
15	2761	2790	2818	2847	2875	2903	2931	2959	2987	3014
16	3041	3068	3095	3122	3148	3175	3201	3227	3253	3279
17	3304	3330	3355	3380	3405	3430	3455	3480	3504	3529
18	3553	3577	3601	3625	3648	3672	3695	3718	3742	3765
19	3798	3810	3833	3856	3878	2900	2923	2945	2967	2989
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404
22	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784
24	3802	3820	3838	3856	3874	3892	3909	3927	3945	3962
25	3979	3997	4014	4031	4048	4065	4082	4099	4115	4133
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757
30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900
31	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899
39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618
46	6628	6637	6646	6655	6665	6675	6684	6693	6702	6712
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893
49	6902	6911	6920	6929	6937	6946	6955	6964	6972	6981
50	7000	7009	7017	7026	7035	7044	7053	7062	7071	7080

50	7070	7080	7090	7100	7110	7120	7130	7140
51	7071	7081	7091	7101	7111	7121	7131	7141
52	7072	7082	7092	7102	7112	7122	7132	7142
53	7073	7083	7093	7103	7113	7123	7133	7143
54	7074	7084	7094	7104	7114	7124	7134	7144
55	7075	7085	7095	7105	7115	7125	7135	7145
56	7076	7086	7096	7106	7116	7126	7136	7146
57	7077	7087	7097	7107	7117	7127	7137	7147
58	7078	7088	7098	7108	7118	7128	7138	7148
59	7079	7089	7099	7109	7119	7129	7139	7149
60	7080	7090	7100	7110	7120	7130	7140	7150
61	7081	7091	7101	7111	7121	7131	7141	7151
62	7082	7092	7102	7112	7122	7132	7142	7152
63	7083	7093	7103	7113	7123	7133	7143	7153
64	7084	7094	7104	7114	7124	7134	7144	7154
65	7085	7095	7105	7115	7125	7135	7145	7155
66	7086	7096	7106	7116	7126	7136	7146	7156
67	7087	7097	7107	7117	7127	7137	7147	7157
68	7088	7098	7108	7118	7128	7138	7148	7158
69	7089	7099	7109	7119	7129	7139	7149	7159
70	7090	7100	7110	7120	7130	7140	7150	7160
71	7091	7101	7111	7121	7131	7141	7151	7161
72	7092	7102	7112	7122	7132	7142	7152	7162
73	7093	7103	7113	7123	7133	7143	7153	7163
74	7094	7104	7114	7124	7134	7144	7154	7164
75	7095	7105	7115	7125	7135	7145	7155	7165
76	7096	7106	7116	7126	7136	7146	7156	7166
77	7097	7107	7117	7127	7137	7147	7157	7167
78	7098	7108	7118	7128	7138	7148	7158	7168
79	7099	7109	7119	7129	7139	7149	7159	7169
80	7100	7110	7120	7130	7140	7150	7160	7170
81	7101	7111	7121	7131	7141	7151	7161	7171
82	7102	7112	7122	7132	7142	7152	7162	7172
83	7103	7113	7123	7133	7143	7153	7163	7173
84	7104	7114	7124	7134	7144	7154	7164	7174
85	7105	7115	7125	7135	7145	7155	7165	7175
86	7106	7116	7126	7136	7146	7156	7166	7176
87	7107	7117	7127	7137	7147	7157	7167	7177
88	7108	7118	7128	7138	7148	7158	7168	7178
89	7109	7119	7129	7139	7149	7159	7169	7179
90	7110	7120	7130	7140	7150	7160	7170	7180
91	7111	7121	7131	7141	7151	7161	7171	7181
92	7112	7122	7132	7142	7152	7162	7172	7182
93	7113	7123	7133	7143	7153	7163	7173	7183
94	7114	7124	7134	7144	7154	7164	7174	7184
95	7115	7125	7135	7145	7155	7165	7175	7185
96	7116	7126	7136	7146	7156	7166	7176	7186
97	7117	7127	7137	7147	7157	7167	7177	7187
98	7118	7128	7138	7148	7158	7168	7178	7188
99	7119	7129	7139	7149	7159	7169	7179	7189

ral types of feedback circuits; each is determined by the signal that is fed back and the manner in which it is fed back to the input circuit. The feedback signal can be proportional to the load current or to the load voltage. To investigate the effects on circuits, we will use the block diagram and schematic diagrams of various schematics. Further simplification is achieved by omitting all components that are bypassed, and analyzing the circuits.

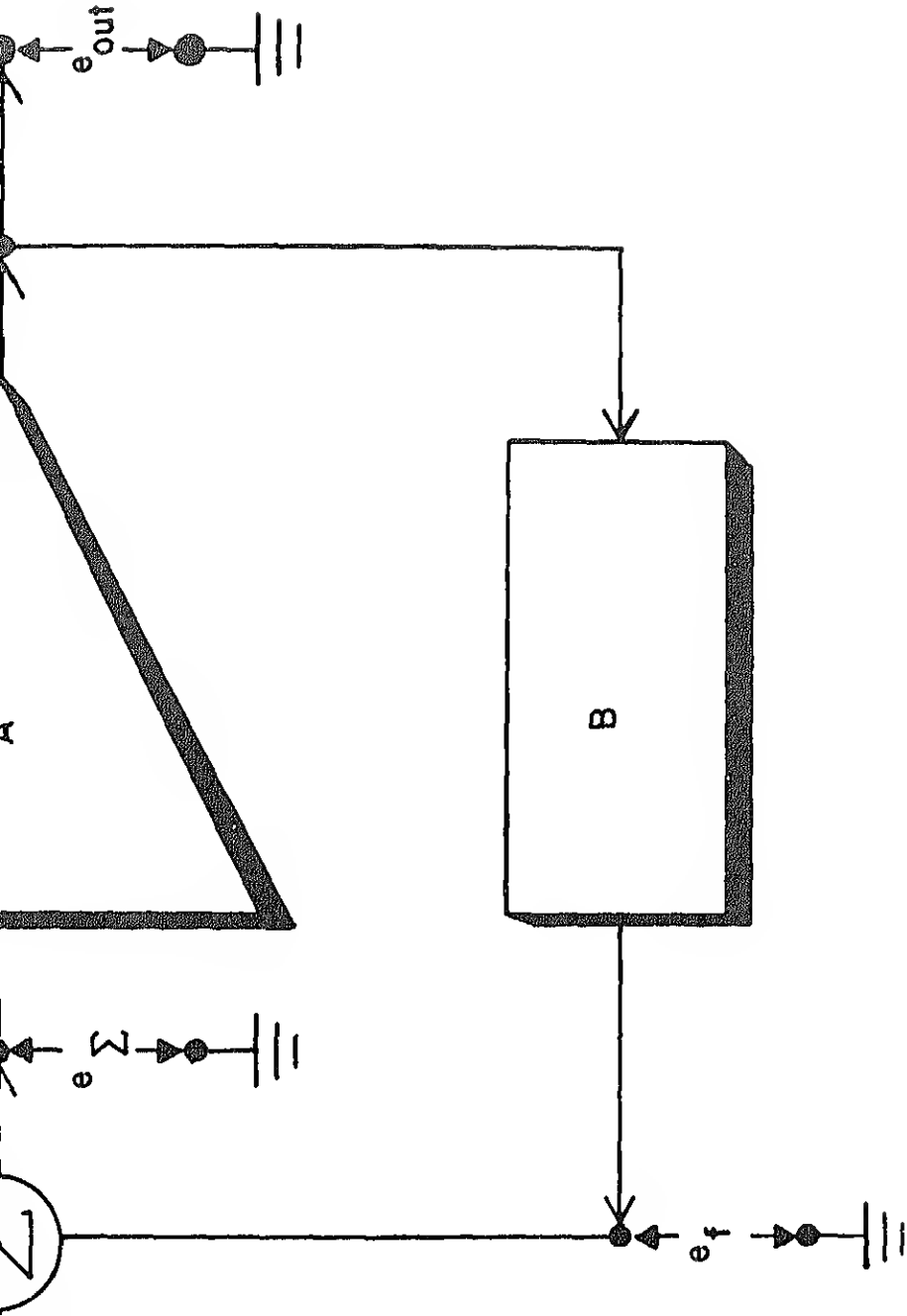
and Osterheld, Essentials of Radio-Electronics, Second Edition, McGraw-Hill Book Company, Inc., 1961.

Feedback Circuits, NAVSHIPS 0967-000-0120, March 1980.



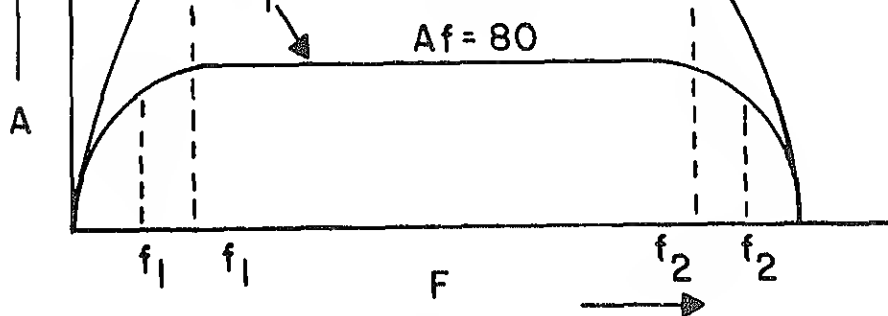
Open-Loop System

Figure 1

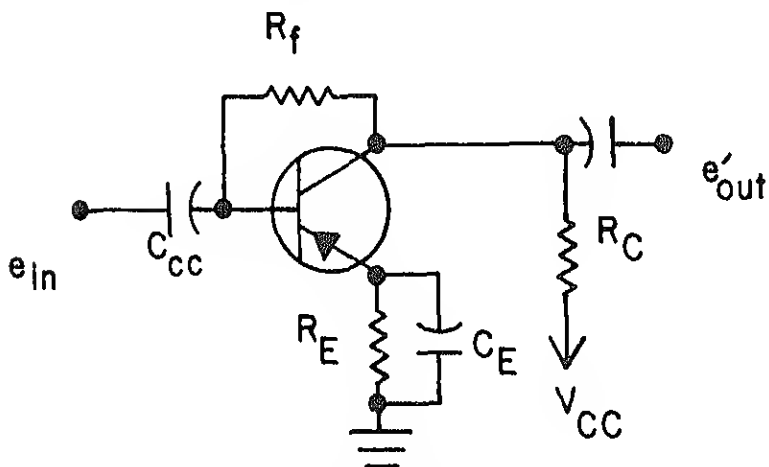


Closed-Loop System

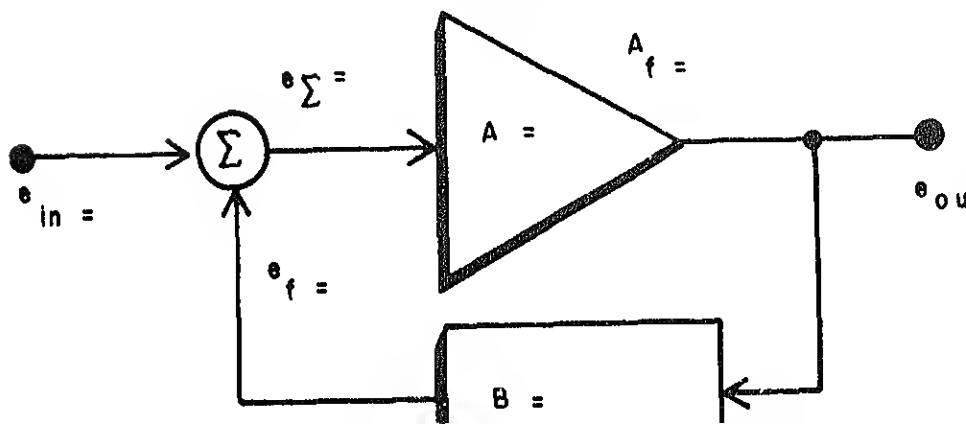
Figure 2

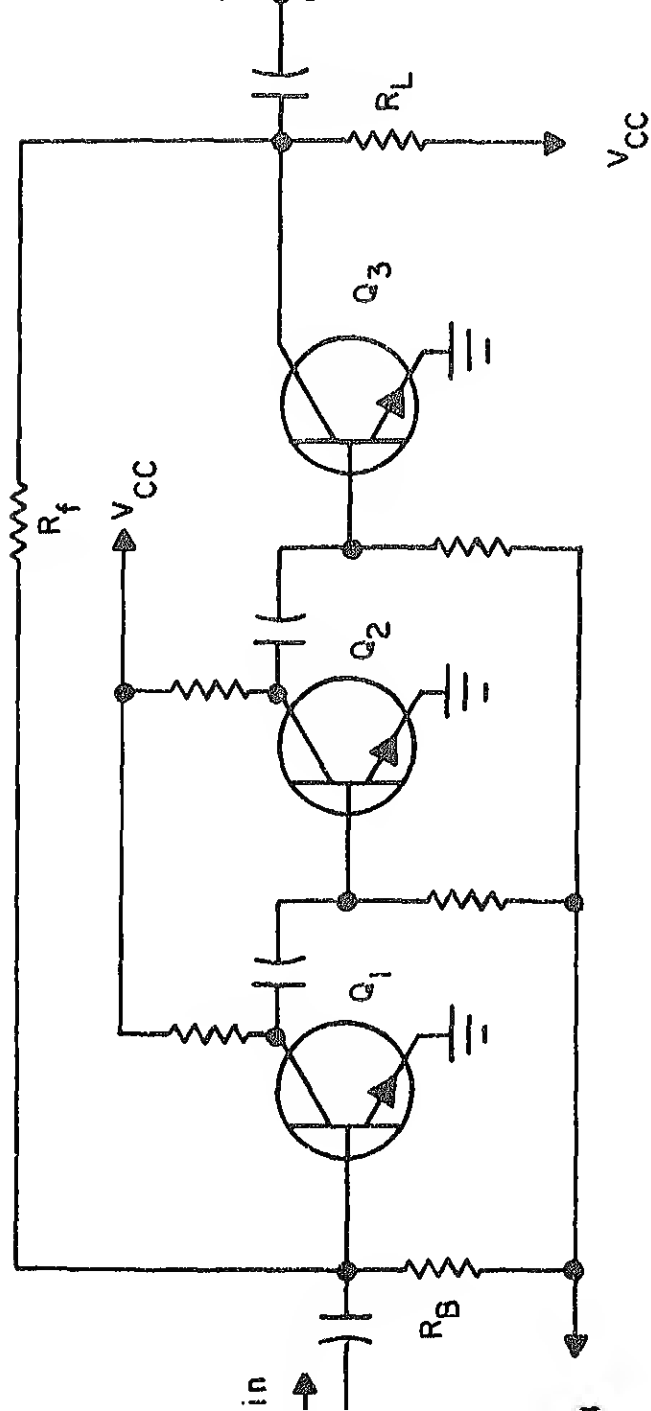


Frequency Response
Figure 3



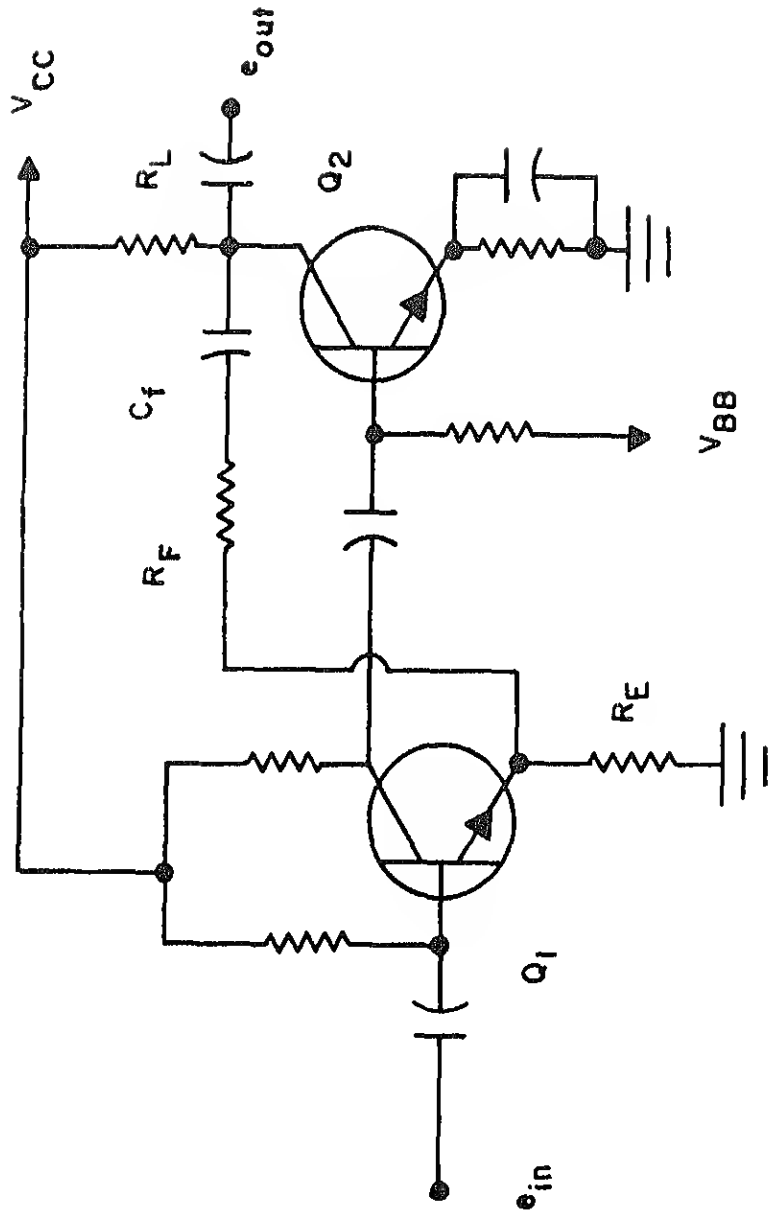
Voltage Feedback
Figure 4



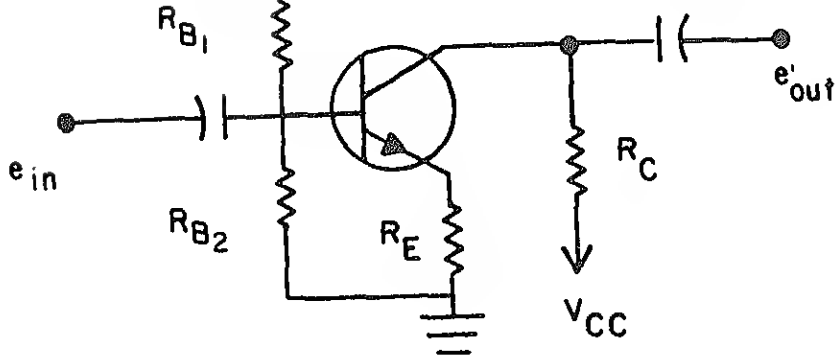


Multi-Stage Shunt-Voltage-Feedback Amplifier

Figure 6



Multi-Stage Shunt-Voltage-Feedback Amplifier



Current Feedback
Figure 8

Gain Formula

Open-loop system implies that no feedback path exists between the input/output terminals. The drive to the gain block (figure 1) is caused by e_{in} alone and not by any action derived from e_{out} .

The basic gain formula is $A_v = \frac{e_{out}}{e_{in}}$. Therefore, $e_{out} = A_v e_{in}$.

A change in A_v , causes a variation in e_{out} .

A closed-loop system implies there is some form of feedback from the output back to the input. It is used to overcome the sensitivity of e_{out} to variation in A_v . The principle of the closed-loop system is based on error detection. It presents a gain (or loss) factor introduced into e'_{out} before it emerges as e_f (the feedback voltage) where e'_o is the output signal with feedback applied. β is indicated in decimal form and may be - or + to indicate whether it is degenerative or regenerative. This will cause e_f to be added or subtract from e_{in} . ϵ is the symbol of the error detector. It will aid in developing e_ϵ which is the algebraic sum of e_{in} and e_f . $e_\epsilon = e_{in} + e_f$, where $e_f = e'_{out}$. The output will follow the input quite closely in a closed-loop system. The drive to the gain block is varied in such a manner as to hold e_ϵ relatively constant.

therefore, $e'_{out} = A_v(e_{in} + \beta e'_{out})$. Multiplying th
 A_v ,

$e'_{out} = A_v e_{in} + A_v \beta e'_{out}$ to collect terms,

$-A_v e_{in} = -e'_{out} + A_v \beta e'_{out}$ or, as is commonly writt

$A_v e_{in} = e'_{out} - A_v \beta e'_{out}$, and

$A_v e_{in} = e'_{out}(1 - A_v \beta)$, dividing,

$$e'_{out} = \frac{A_v e_{in}}{1 - A_v \beta}$$

The closed loop gain (with feedback) is A_f .

$$A_f = \frac{e'_{out}}{e_{in}} \text{ or as has been resolved previously,}$$

$$A_f = \frac{A_v e_{in}}{1 - A_v \beta} + e_{in} \text{ which could be rewritten as}$$

$$A_f = \frac{A_v}{1 - A_v \beta} = \text{closed-loop gain.}$$

Negative Feedback Amplifiers

4. General

1. There are several types of feedback circuits; determined by the nature of the signal that is and the manner in which it is applied to the i circuit. Thus the feedback signal can be prop to the load current or to the load voltage.
2. The signal fed back can be applied in series o shunt with the input circuit. It, therefore, that there are four basic types of feedback ci and they are:

1. The current output-series input.

The input and output impedances of these four types of feedback circuits are affected differently by the applied feedback, but their individual gains will be affected similarly by the applied feedback.

To investigate these effects, we will use the block diagram form and basic schematic diagrams. The blocks will contain both the signal input and output leads, plus the common input and output leads for clarification. The assumptions made are that the basic amplifier is unilateral; that is, there is no interaction between its input and output terminal pairs and the input/output impedance of the feedback network is sufficiently high to ensure that it does not load the basic amplifier.

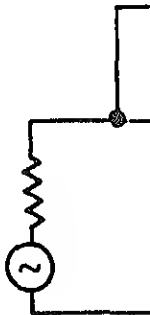
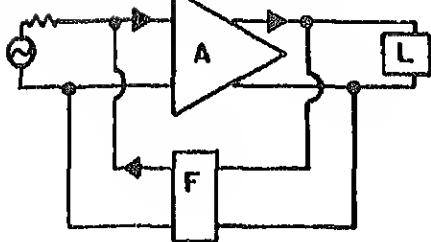
Further, simplification is obtained by omitting all components that are bypassed, those capacitors with negligible reactance at mid-frequencies, and the d-c biasing circuits. The signal generator is always displayed along with its internal resistance.

Large output-shunt input

Figure 9a shows the feedback block, "F", across the load and the input. Any change in voltage across the load is sampled and a portion of this sample is applied across, or in shunt with the input terminals. Note, in the following sections of figure 9, the feedback resistor is in series with the input resistance of the first stage.

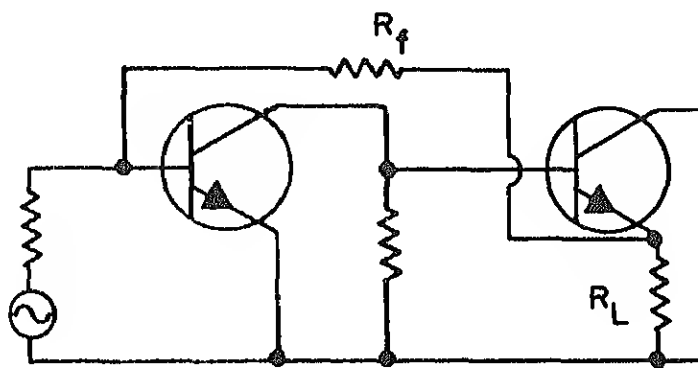
If the feedback block is in shunt with both the input/output terminals of the gain-block, then the input/output resistance must be lower with this type of feedback. Also, the polarity difference between the input signal and feedback signal is 180° . The gain-block resembles a constant-voltage source and is rendered insensitive to device parameter changes, relative to the amount of feedback applied.

In the schematics shown, blocking capacitors would isolate the d-c voltages from upsetting the bias levels. However, with careful design, the bias levels can be set

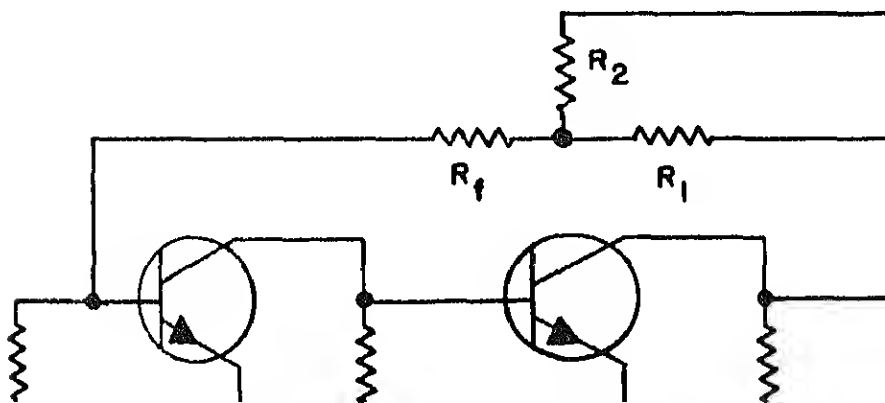


Voltage output-shunt input

(a)



(c)



9b represents a single stage with local feedback. Figure 9c is a CE to CC configuration, with the resistance extremely low. Figure 9d shows three of CE amplifiers. The load for the output stage, R_1 and R_2 , in series, are in parallel with R_L , the portion of the output voltage at their junction fed back through R_f , which is in series with the R_1 of first stage.

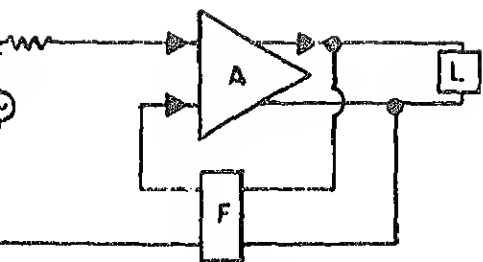
In the cited cases, the input driving signal has been effectively reduced, reducing the output signal. Both input and output resistances are lowered. Bandwidth increased, distortion reduced, stability increased, periodic noise reduced.

Output-series input

Figure 10a is the block diagram of this feedback arrangement. The voltage across the load is sampled and a portion of it, called the feedback voltage, is applied in series with the input signal. The polarity of the feedback signal is such that it will oppose the input signal, reducing the effective drive to the gain-block.

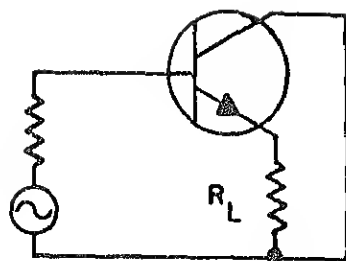
Figure 10b shows the extreme case of 100% voltage feedback in an emitter follower or CC amplifier. Reasoning leads to the conclusion that this could not be 100% degeneration, or else there would be no output. The only way to cause 100% degeneration would be to throw the power "on/off" switch in the "off" position.

Figure 10c shows two CE amplifiers and figure 10d has an emitter follower stage to effect a much lower output resistance. In all cases shown so far, the output circuits are controlled by the feedback circuits, lowering the output resistances and keeping the output signals constant, with variations in the gain-block. However, in figure 10, the feedback voltage is applied in series with the input signal, thus greatly reducing the input driving signal to the gain-block. This has the effect of increasing the input resistance. The polarity of the feedback signal is in series with the input signal and opposes its action. Therefore, the input resistance is increased while the output resistance is lowered. With this application of

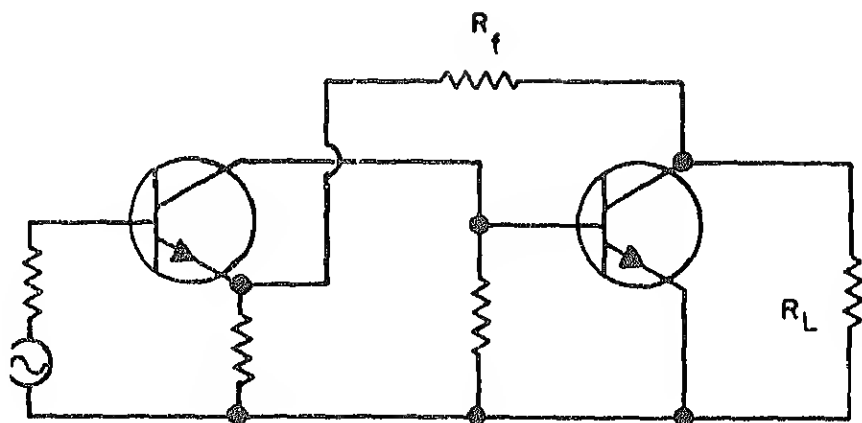


voltage output-series input

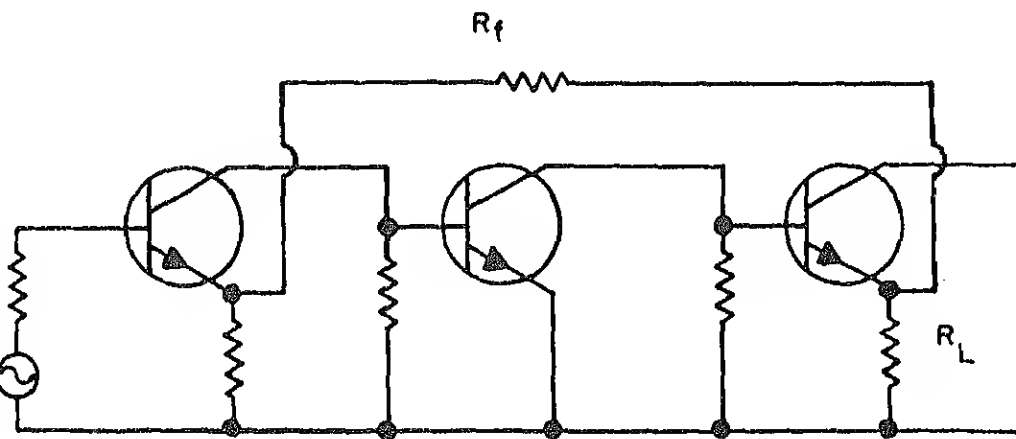
(a)



(b)



(c)



LOCK.

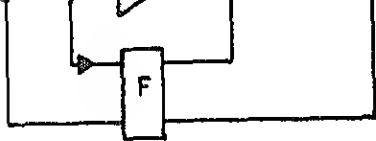
Figure 11b shows a CE to CE amplifier with the output resistance being increased and the input resistance lowered by this type of feedback. The feedback signal is taken from R_1 , which samples the output load current. It is then applied through R_f in series with the R_i of the first stage. Since this type of feedback tends to keep the output current constant, the gain-block resembles a constant-current generator with its high output resistance.

In figure 11c, R_2 samples the load current and is also part of the load resistance of the last stage. Load-current variations develop the feedback signal voltage across R_1 . The gain, stability, distortion, and noise with this type of feedback application are similar to the others discussed.

Current output-series input

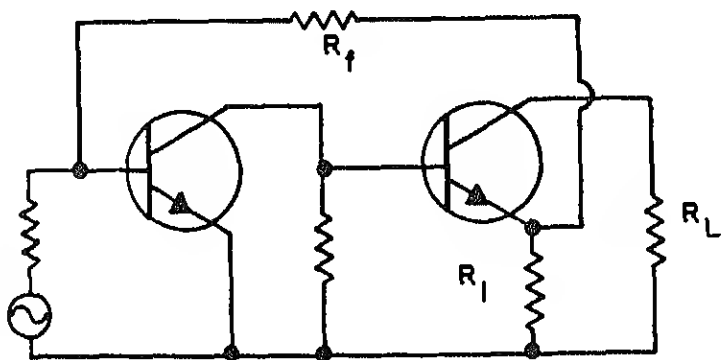
Figure 12a shows a block diagram with the output load current flowing through the feedback sampling circuit and the feedback voltage developed by the load current which is applied in series with the input signal.

This application maintains a constant output current and greatly controls the input driving signal current. The input and output resistances are increased by this type of feedback application. Figure 12b shows the CE amplifier with the resistor in the emitter leg. It is strongly emphasized here that this resistor will prevent thermal runaway. Reasoning reveals that if the output current tends to "run", the feedback voltage it develops across the resistor reduces the forward bias, resulting in slowing the "run" to a "crawl" and a "stand still." This resistor, when bypassed, allows maximum stage gain. However, when unbypassed, it introduces degenerative feedback to the applied a-c signal and improves the stability, bandwidth, distortion, and noise figure as discussed previously.

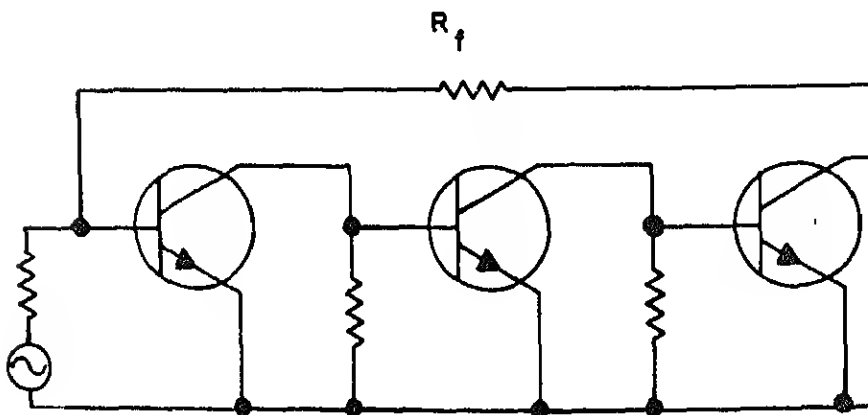


Current output-shunt input

(a)



(b)



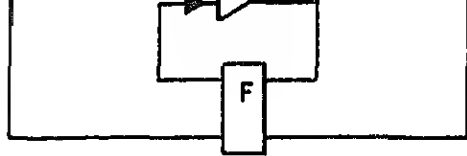
(c)

al feedback

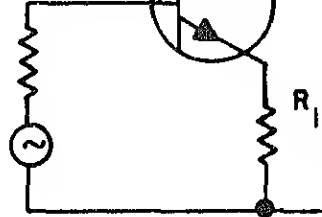
ng on the requirements, feedback can alter slightly
tically, the input/output resistance of any type of
er. The characteristics of one can be overshadowed
ner, depending on the amount of each applied.

10c is voltage output-series input, but the emitter
first stage introduces a small amount of current
series input, locally. This, of course, is
able, because the emitter of the first stage must
e ground for injection of the overall feedback
The same holds true for figure 10d.

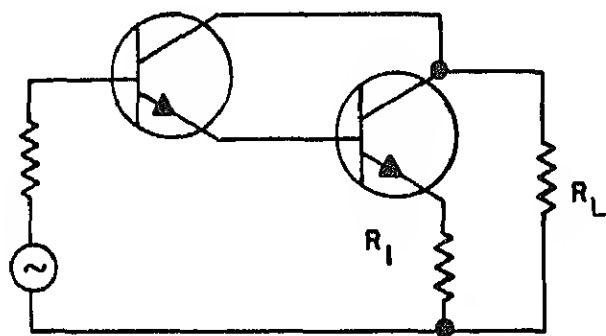
plexities which reactive components add to feedback
great to be analyzed in this allotted time. The
ian will see various types and applications during
ubleshooting procedures. With experience and
studies, you will become familiar with the forever
feedback circuits.



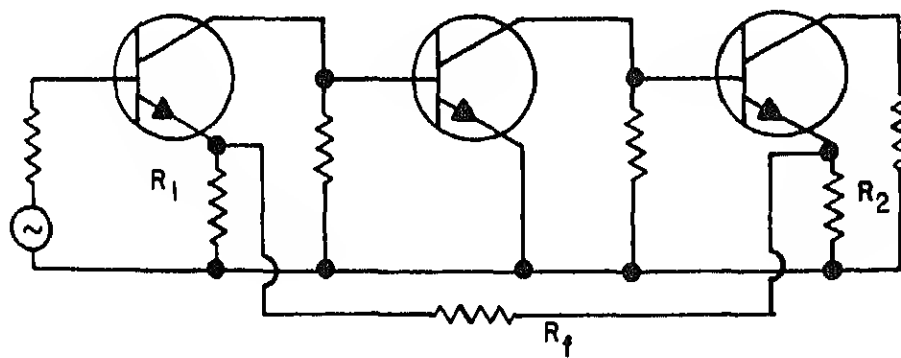
(a)



(b)



(c)



s of Radio-Electronics, Slurzburg & Osterheld, McGraw-
Second Edition, 1961.

c Circuits, NAVSHIPS 0967-000-0120, March 1980.

TLINE:

pen-Loop System

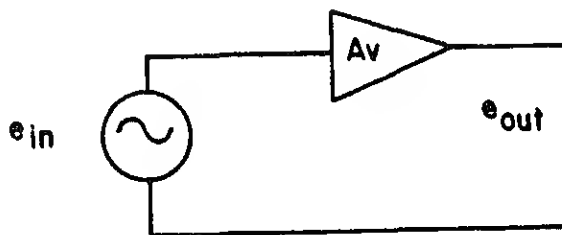
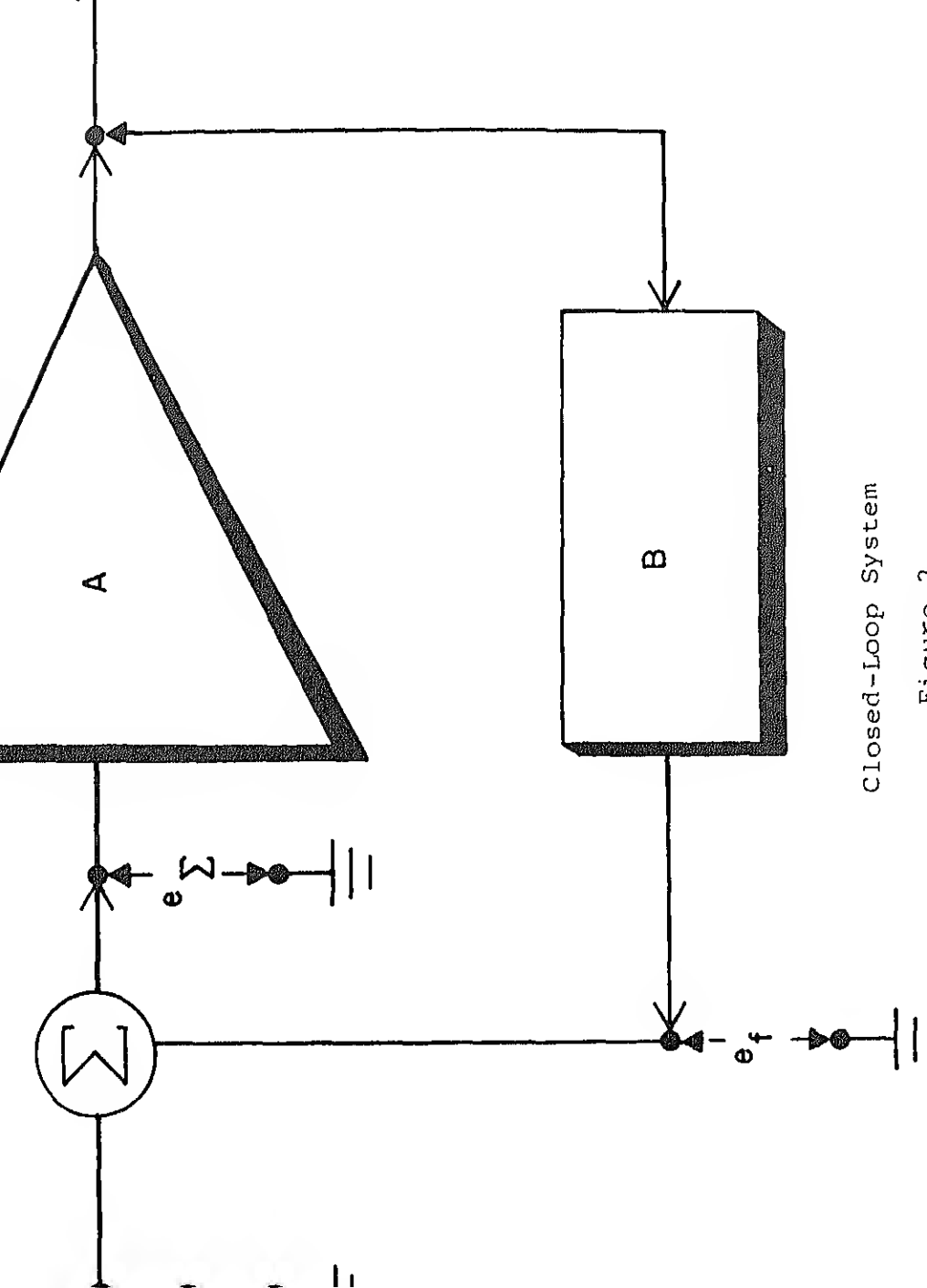


Figure 1

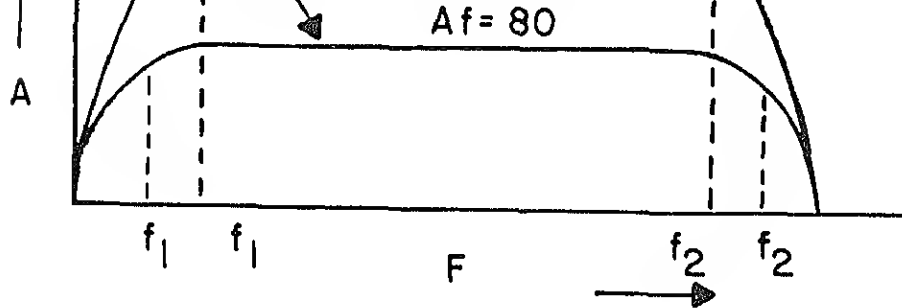


Closed-Loop System

Figure 2

III. Classes and Types of Feedback

Characteristics



Frequency Response
Figure 3

Transistor Circuits

A. Single stage voltage feedback

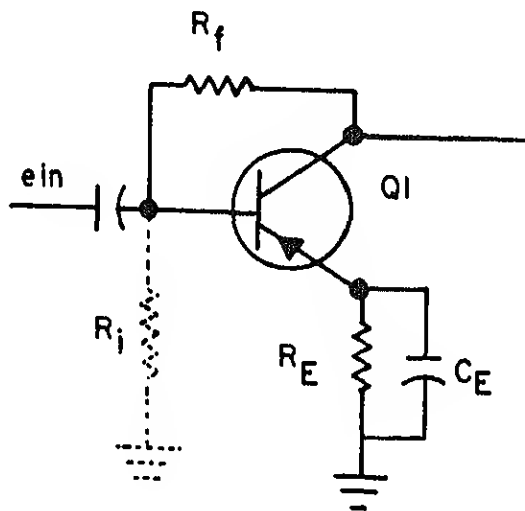
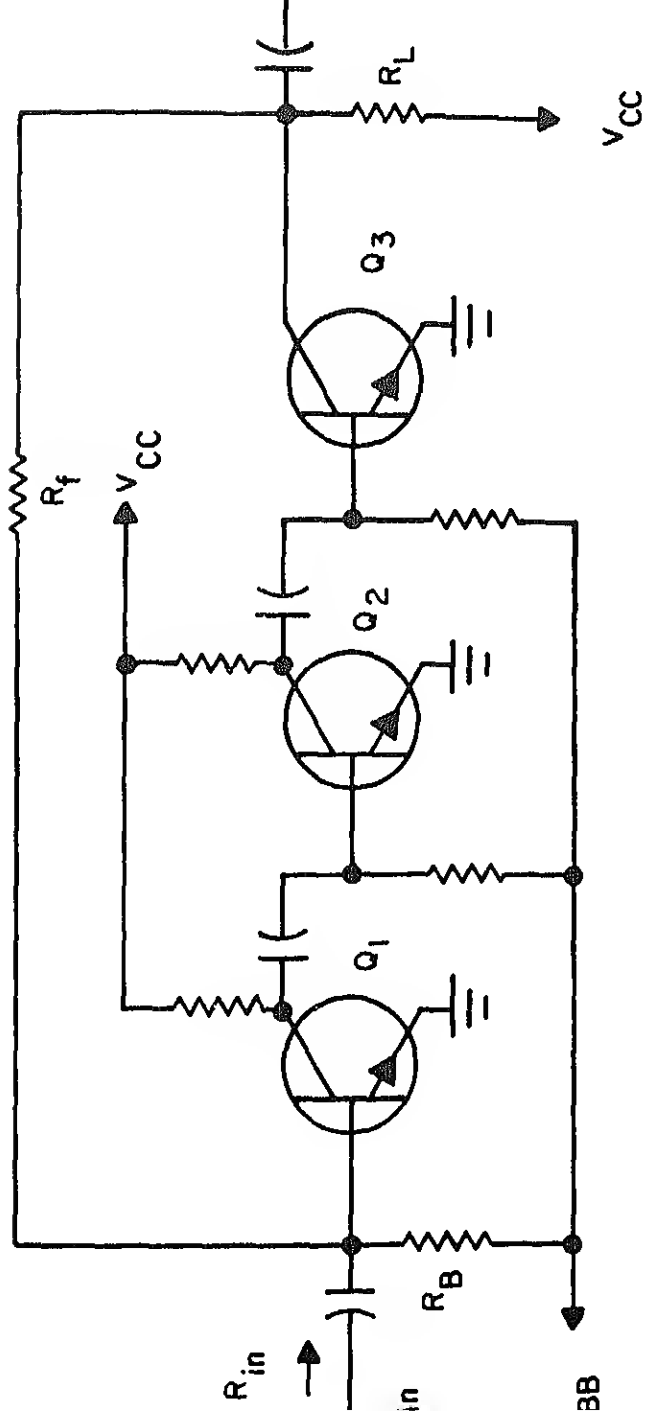


Figure 4 - Single-Stage-V
Feedback.

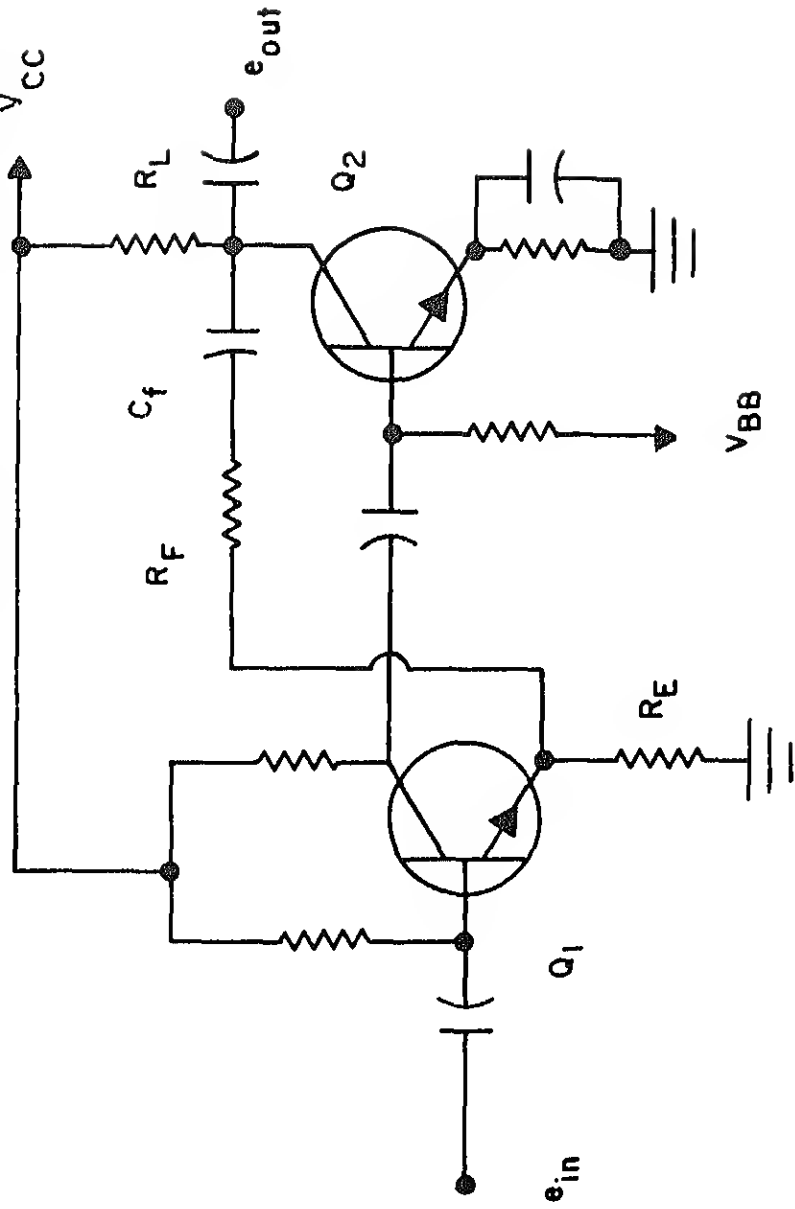
c. Multistage voltage feedback (series)



Multistage Shunt-Voltage-Feedback Amplifier

Figure 5

D. Current feedback



Multistage Series-Voltage-Feedback Amplifier

Figure 6

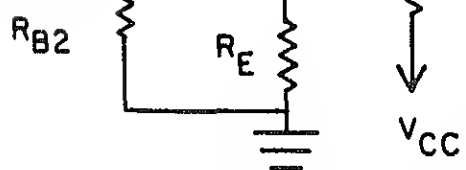


Figure 7 - Current Fee

E. Combination feedback

systems, require the amplification of d-c voltages. A single stage of amplification is not sufficient to bring such signals to the required values; therefore, multiple stages of coupling are necessary to ensure that maximum energy is required. This lesson on direct coupled amplifiers is essential for the

Kiver, Transistor and Integrated Electronics.
 McGraw-Hill Book Company, Fourth Edition, 1972.

Shrader, Electronic Communication, McGraw-Hill Book
 Company, Fourth Edition, 1980.

The following figures are labeled by title and will assist you in following the instructor through the lesson.

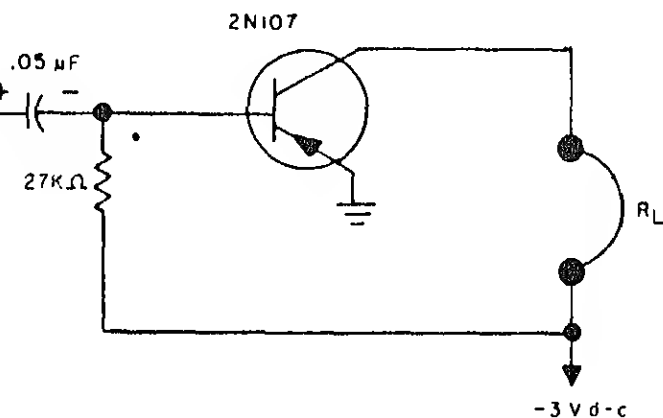


Figure 1

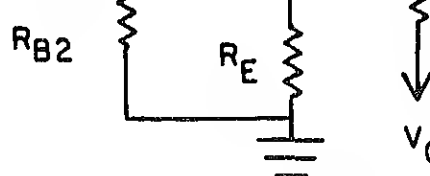


Figure 7 - Current I

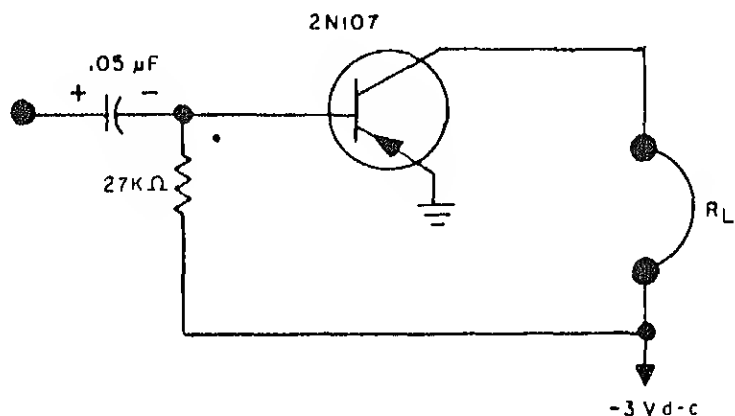
E. Combination feedback

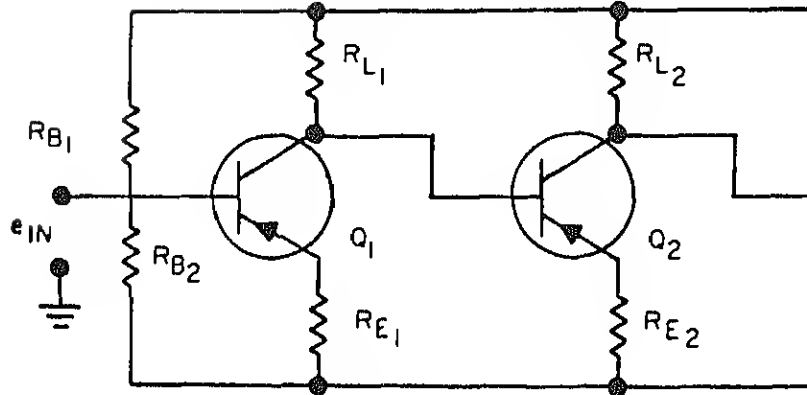
onic systems, ranging from voltage regulators to communication systems, require the amplification of d-c voltage. One stage of amplification is not sufficient to bring the level of such signals to the required values; therefore, multiple stages of coupling are necessary to ensure that maximum energy is required. This lesson on direct-coupled operational amplifiers is essential for the

S. Kiver, Transistor and Integrated Electronics, McGraw-Hill Book Company, Fourth Edition, 1972.

L. Shrader, Electronic Communication, McGraw-Hill Book Company, Fourth Edition, 1980.

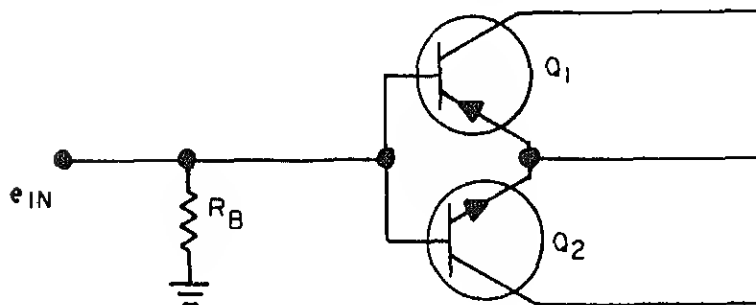
Following figures are labeled by title and will assist you in following the instructor through the lesson.





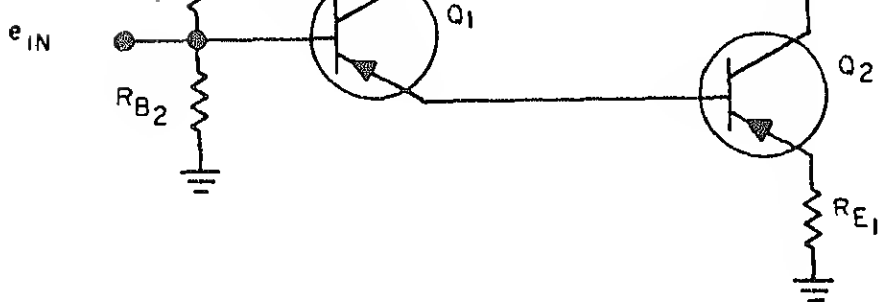
Cascaded CE d-c Amplifier.

Figure 2



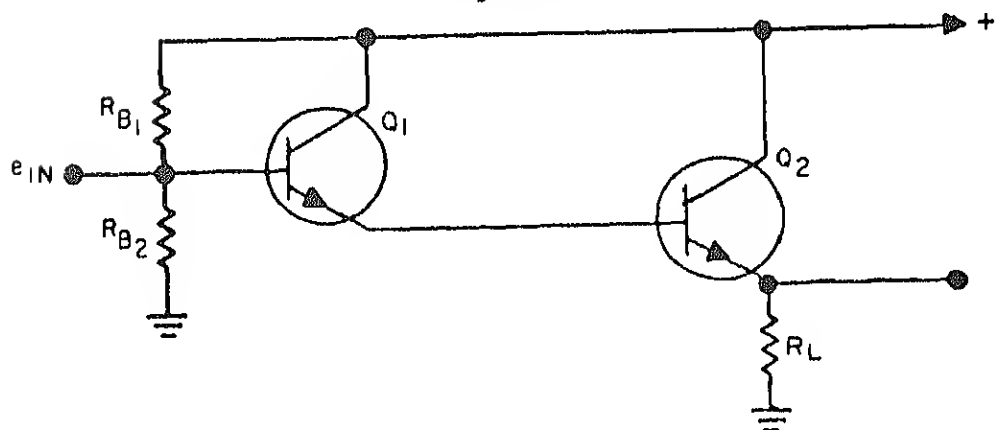
Complementary Symmetry

Figure 3



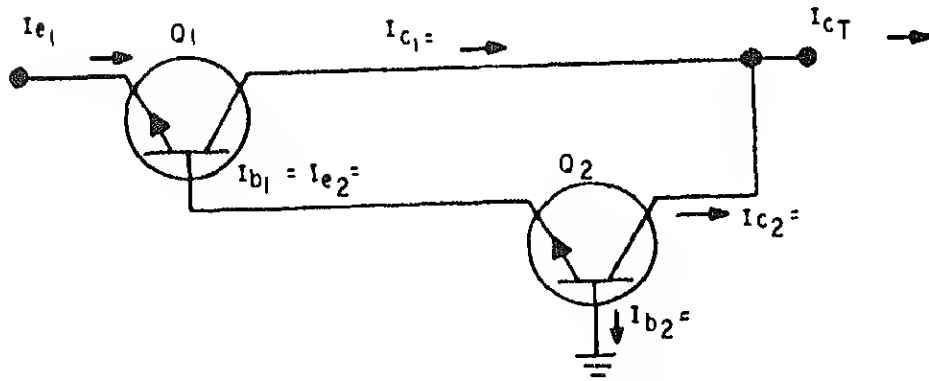
Compound-Connected

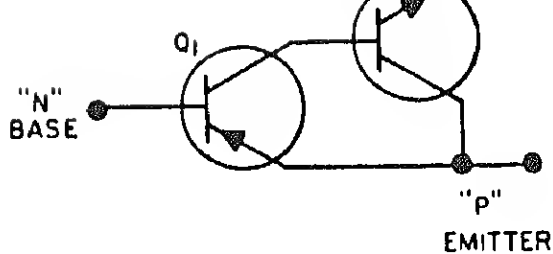
Figure 4



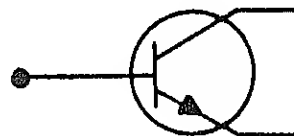
Darlington Circuit.

Figure 5





a
"PNP"



b
"NPN"

Complementary Darlington's

Figure 7

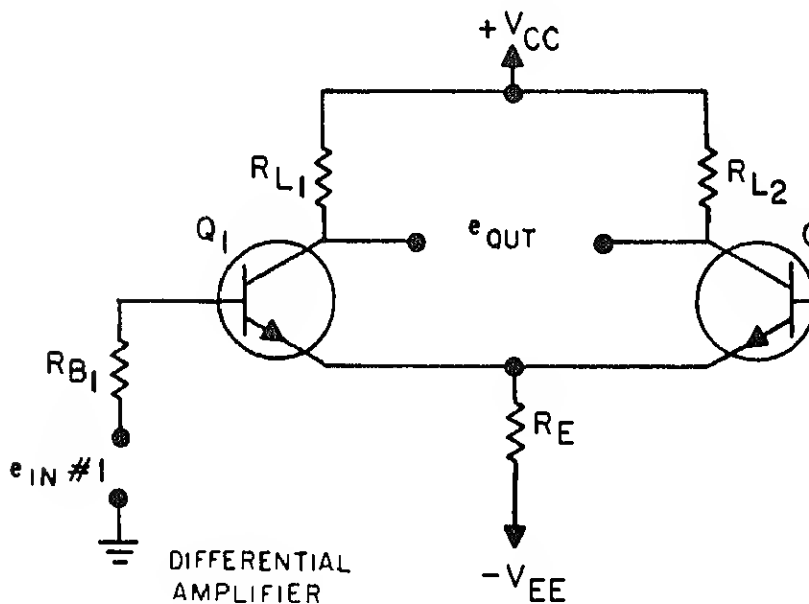


Figure 8--Modulated a-c Carrier

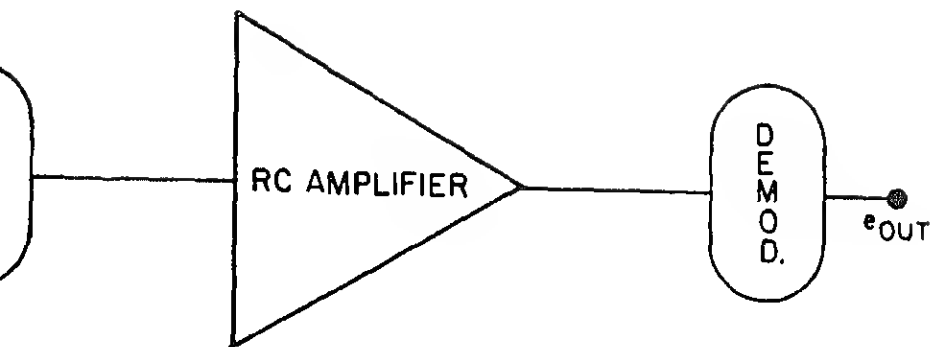


Figure 9--Chopper Amplifier

ED AUDIO AMPLIFIER

ion

Direct-coupled audio amplifier is used where high gain audio frequencies or amplification of direct (zero frequency) is desired. The direct-coupled amplifier is also used where it is desired to avoid the loss of frequencies through a coupling network. This circuit has numerous applications, particularly in measuring or test instruments, and industrial equipment.

Characteristics

1. common-emitter circuit for high gain.

2. Usually requires thermal stabilization to prevent drift.

3. Frequency response extends to zero frequency (direct current).

4. Responds equally well to pulses or sine waveforms.

Analysis

is also applied to another element. No increase or decrease is self-correcting in the feedback resistor. In most instances, however, the problem becomes a major problem if more than two amplification are cascaded.

2. Germanium transistors are more subject to instability than are silicon transistors. In this case it is usually necessary to provide a temperature compensation if the temperature varies more than a few degrees centigrade. The complexity of the compensation circuitry is dependent upon the amount of compensation required. Because of the rapid changes which are occurring in the semiconductor field, it is likely that temperature compensation will be eliminated or minimized to some degree in the future. Even so, however, the limitation of direct coupling still remains. The necessity for cumulatively increasing the bias and operating values as each stage is cascaded is a disadvantage. The use of low bias and collector voltages prevents the use of a wide range than can be obtained with the electron tube, and the transistor, like the electron tube, has a limited maximum breakdown or reverse potential.
3. In addition, noise is a problem, since the amplifier amplifies any internal noise as well as the noise of the transistors. Transistors are prone to produce greater noise at lower audio frequencies. Thus, the ability of the amplifier to extend its response to low frequencies is normally available through other coupling methods is somewhat nullified by the amplification of the noise in the transistor. Generally speaking, the low-frequency response of the d-c amplifier is limited only by the signal-to-noise ratio. The high-frequency response is limited by the frequency response characteristics of the transistor.
4. In the direct-coupled amplifier, the collector of the first input stage is directly connected to the base of the second amplifier stage; therefore, any collector current variation also appears at the base of the second stage, just as if it were a change in the input signal. The transistor in the second stage has no discriminating between actual input signal and the collector current variation of the first stage.

an output signal. Similarly, a change in in any stage or on any element will be proportionally, and a change of output will with changes in bias levels normally occur as a temperature variations, aging, difference in characteristic due to manufacturing or changes in transistor leakage current, and d to as drift.

on of the forward-bias characteristics of a manium diode with temperature is shown in The forward-bias variation is usually s a change in bias voltage with temperature nt forward-bias current. It is usually becomes significant because of the large on it receives because of the direct-coupling .

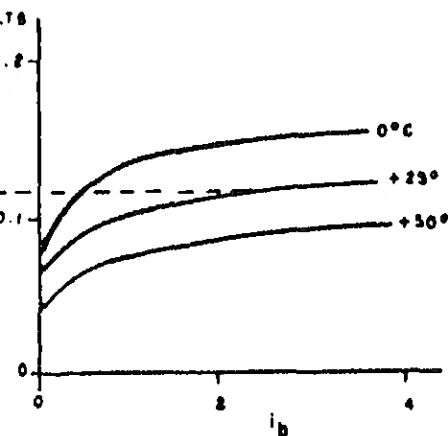
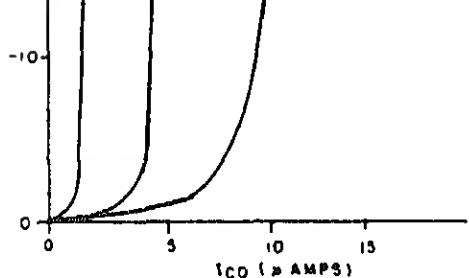


Figure 10

anner in which the collector-base diode varies erse saturation current with temperature is own in figure 11 (for a typical germanium stor). In this instance, the figure shows e reverse-current characteristic is highly ture-dependent, and relatively large current ons are produced as the empe ature is



VARIATION OF COLLECTOR-BASE DIODE REVERSE CURRENT

Figure 11

8. In a similar manner, it can be shown that the current transfer characteristic of a germanium transistor also varies with temperature; however, in this case the gain can either increase or decrease with temperature (silicon types generally increase with temperature). The percentage variation in gain with temperature varies greatly with the operating conditions. Many units show a change in sign as well. The gain variation of a silicon type may be as much as ten times that of a germanium type. Thus, it is evident that the major sources of drift in transistor circuits are changes in the d-c properties of the collector-emitter-base diodes, and changes in the current transfer ratio. Generally speaking, in the design and operation and performance of germanium and silicon transistors, it can be said that at temperatures above that of the reference temperature, T_0 , the drift is comparable. At and above the reference temperature, the silicon type tends to have lower drift. The reference temperature for silicon is 100° centigrade and for germanium is 60° centigrade. With low source resistance, low values of drift are obtained at low temperatures. With high source resistance, the best performance is obtained at temperatures where the reverse-saturation current may be neglected.

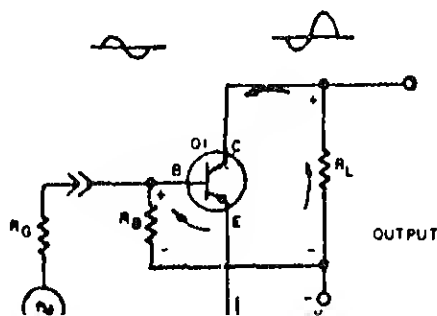
9. In d-c amplifiers, low drift is obtained with low values of collector current; this is achieved by keeping the reverse-leakage current by keeping the voltage across the collector and the base at a low value. If there is a forward bias for reverse current,

is somewhat limited. In single-ended amplifier stages, both the current drift and the voltage drift in the second stage tend to help cancel the input-stage drift; in a differential d-c amplifier, however, the drift in the second stage may either aid or oppose that of stage 1, depending upon the design.

Despite the apparent disadvantages of the d-c amplifier, it does produce (for a two- or three-stage unit) high gain and good fidelity, particularly in the low-frequency portion of the spectrum. It also provides amplification with as few parts as possible; thus, it is economical to build. In actual practice, the d-c amplifier is usually limited to one or two stages of amplification because of drift, especially where d-c must be amplified or where frequencies of 10 to 12 Hz are of importance. To overcome the effects of drift in d-c amplifiers, a special "chopper amplifier" has been developed; this amplifier converts the d-c into a-c so that the stages can be isolated and thus prevent the cumulative drift which normally occurs. This is a special type of amplifier, which will be discussed later in this section of the Information Sheet.

Bit Operation

Basic Circuit. The schematic of a basic common-emitter d-c amplifier is shown in figure 12. The input signal is represented by the AF generator with an internal resistance equal to R_{INT} . The input signal is applied between base and emitter. Transistor Q_1 is biased by

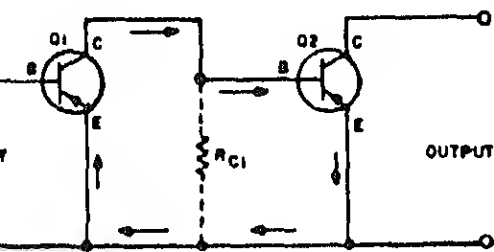


opposes the bias between base and collector, normally chosen for class A operation. The electron current flow through the collector resistor, R_L , is indicated by the arrows, of the resulting d-c voltage across the load is as shown. When the positive alternation of the input signal is applied to the base, the base-emitter voltage is reduced (since the signal and bias voltage are of opposite polarity). Because the base-emitter voltage is now less than the normal value, the electron flow from the emitter to the collector is lower and the electron flow through the output load resistor is reduced. The decrease in voltage drop across R_L produces a negative swing and, consequently, a negative output signal across R_L . As the input signal goes negative, the bias potential is increased by the input signals, and as the base-emitter voltage is increased, more hole current flows to the emitter. This produces more electron flow through the collector circuit, increasing the voltage drop across R_L and produces a positive output-signal swing during that the input signal is negative. This effect produces an opposite-polarity output signal (referred to as a 180° phase reversal). Since the load for both d-c and a-c, there is only one load line, and any internal noise voltages flowing through the load resistor add to the developed output voltage. Since the output across R_L is applied directly to the base of the next stage, it can be seen that noise components appear across the following input. In an a-c coupled circuit, these noise components consisting of d-c or very low frequencies, are not eliminated (blocked by the coupling capacitor). Noise components are produced by thermal noise and also result from electron flow through the collector resistor. They include the so-called white noise generated by diffusion-recombination effects in the transistor (similar to shot noise in the vacuum tube) and surface and leakage noise from the transistor. This is sometimes referred to as semiconductor noise to distinguish it from white noise. Such noise is mostly confined to the region of from 1 to 100 kHz, white noise (in the audio range), with the a-c noise predominating and increasing for frequencies above 1 kHz. The d-c noise results from su

er hand, with proper input and output match-
 um gain is obtained in the stage; moreover,
 oupling network to create a loss between
 aximum output and efficiency are produced.
 frequencies are present, including d-c (zero
 and are applied equally to the next stage, it
 derstood why the d-c amplifier presents maximum
 excellent frequency response, particularly at
 frequencies.

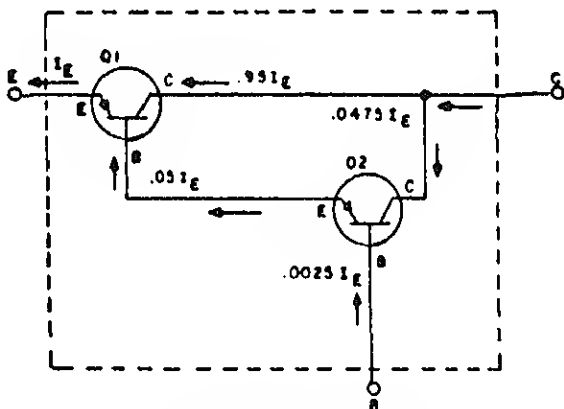
stages. Because of the high gain possible per
 y applications require only a single stage of
 ed amplification. Where more than one stage is
 transistors offer circuit arrangements that
 possible with electron tubes. For example,
 e use of complementary symmetry, it is
 o connect the collector of the input stage
 o the input of the second stage without dis-
 as arrangements, and to use the same supply.
 alternate arrangements of NPN and PNP tran-
 only one supply is needed. Recall that in the
 oe d-c amplifier, as each stage progresses, the
 age is increased, with the grid being tapped
 the preceding-stage plate voltage to obtain

Only tandem arrangements of similar-type
 s can follow this principle. The term comple-
 mmetry is derived from the fact that the NPN
 r is the complement of the PNP transistor, with
 its operating identically, but with opposite
 s. Figure 13 shows a simple direct-coupling
 ing complementary symmetry.



this resistor is not needed and proper saving in components. To do this, of course, the resistors must be of opposite types (NPN

4. By the use of a special compounding connection, transistors may be employed as a special amplifier to obtain linearity and almost perfect linearity (alpha). Figure 14 shows the compound connection, using the common-base configuration.



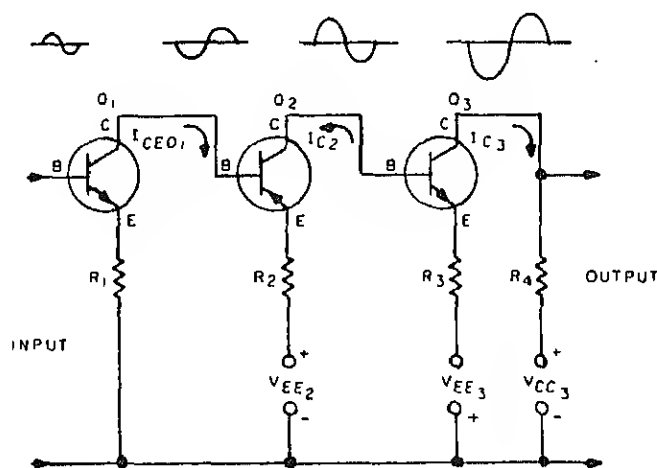
COMPOUND CONNECTION

Figure 14

Note that the input to the second stage is the collector current of the first stage. Effectively, the input impedance is the series combination of the two transistors, while the outputs are in parallel. This circuit is roughly analogous to the push-pull tube circuit. Actually, this circuit is a single-transistor compounded-type circuit in a common-base, and collector resistors used externally. The direction and relative values of currents are shown in the figure, assuming the use of two transistors with an equal a_{fb} of .95. When these values are substituted for a_{fe} , the total combination value (.991) is a gain of 399 as compared with a_{fe} of 1 for a single transistor, or more than the normal gain in cascade ($19 \times 19 = 381$). Comp

an amplifier, or are used as the d-c amplifier in a
age-regulator circuit.

typical three-stage, single-ended d-c amplifier is
own in figure 15. It represents the minimum of parts
d-c supplies needed for a high-gain, three-stage
plementary-symmetry type of d-c amplifier for small
al applications.



TYPICAL THREE-STAG AMPLIFIER

Figure 15

shown, the base of the input stage is completed
ough the input device, it is effectively open, it has
driving voltage, and zero base current exists. The
lector current, I_{CEO1} , flows through the base of
ge 2, which is biased by supply V_{EE2} in series with
emitter of stage 2. Since stage 1 uses a NPN tran-
or, the positive emitter bias of stage 2 is of the
per polarity to act as collector voltage for Q1. Any
nge in the collector current of stage 1 appears at
collector of stage 2 in amplified form; that is,
 $= B_2 I_{CEO1}$, where B_2 is the current gain of stage 2.
e 2 uses a PNP transistor; therefore, by comple-
tary symmetry, stage 3 must also be an NPN stage

act as emitter-swamping resistors to help amplifier with respect to temperature variations.

Assuming that the input stage has a collector current of 5 μ A and assuming a gain of 38, the second stage will have a collector current of 190 μ A. With the third stage collector current will be clear that any slight change in the current caused by temperature or noise will be greatly amplified and appear at the output of stage 3. With this in mind, for stability and amplification, therefore, it is mandatory that such an amplifier be temperature compensated, even if room temperatures do not vary excessively. Naturally, the amplitude of the signal must be limited if true fidelity is to be obtained. Driving the transistor into cutoff or saturation would clip the peaks of the signal, just as in an electron-tube operation. It is also essential that low-noise transistors must be used; otherwise the noise might mask the signal. Note that in this circuit the small emitter bias of stage 2 operates as the emitter voltage of stage 1. Low collector voltage will help to minimize noise generated in the input stage.

ional amplifier is an extremely efficient and device. Its applications span the broad electronic illing requirements for analog instrumentation, utation, and special system design.

, the term "Operational Amplifier" was used in to describe amplifiers that performed various al operations. It was found that the amplification feedback around a high gain d-c amplifier would circuit with precise gain characteristics that nly on the type and amount of feedback used. By the ection of feedback components, operational amplifier ould be used to add, subtract, multiply, divide, and differentiate.

l amplifier techniques became more widely known, it t that these feedback techniques could be used in ol and instrumentation applications. Today, the of operational amplifiers has been extended to ch applications as d-c amplifiers, a-c amplifiers, s, servoamplifier, deflection yoke drivers, and a ners.

perational amplifier can do is limited only by the n and ingenuity of the user. With a good working of its characteristics, you will be able to exploit the useful properties of operational amplifiers.

Integrated Electronics, Kiver, McGraw-Hill, Fourth
pages 271-305

- An operational amplifier is a high gain, direct-c) amplifier utilizing degenerative feedback for its amplification factor.

amplifier gain is less than one, then the operational amplifier is d. For example, an amplifier with a gain of .5 will multiply its input by 1/2.

2. Gain itself is determined by the ratio of input to output voltage.

$A = \frac{E_o}{E_{in}}$. The voltage gain of an operational amplifier is a ratio of $E_o : E_{in}$.

3. However, the amplifiers do improve the performance of various computing loops, by accomplishing the reversing the sign of a voltage with or without a scale factor; isolate or eliminate the loading of one computing element from another; provide a voltage to the algebraic sum of two or more input voltages; perform the various functions performed by operational amplifiers; they are called by several names; computing amplifier, isolation amplifier, feedback amplifier, and summing amplifier.

C. Functional analysis

1. Amplifier section

- a. In order to better understand operational amplifiers, we will first go through the different parts of an operational amplifier.
- b. The heart of the operational amplifier is the input section. It is represented by the triangle in Figure 1. It contains an odd number of direct-coupled amplifiers, usually three or five stages. An odd number of amplifiers are required to provide an odd number of phase shift from input to output. The output voltage will always be opposite or inverted with respect to the input polarity to provide negative feedback.
- c. Open loop gain, that is the gain of the amplifier without feedback, is from 1×10^3 to 2×10^3 or usually around 50×10^3 or 50 k; 92 dB.

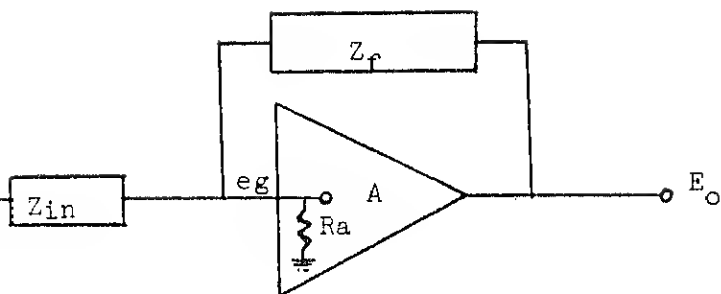


Figure 1

Figure 2, is an expanded view of the amplifier in block diagram form.

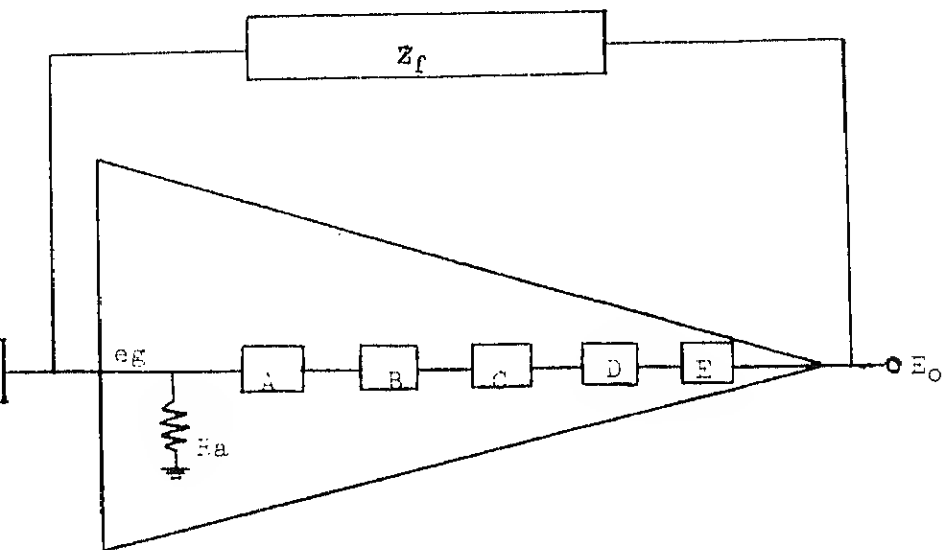


Figure 2

- f. Blocks B through D are the d-c amplifiers stage gain of only 100 then the over gain circuit would be $1,000,000 \times 100 = 100,000,000$. Because there is an odd number of stages, phase inversion always occurs.
- g. The final stage again will be either a cathode follower or an emitter follower for further isolation.
- h. R_a is the base or grid resistor for the final stage. It develops e_g or the input potential for the next section.
- i. The effective input impedance is very low and is found by the formula Z_{in} (of amplifier section). Some typical values are:

$$Z_f = 1 \text{ megohm}$$

$$A = 50k$$

If they are put into the formula, then $\frac{1}{1+A}$ is approximately. The effective input impedance is very low.

- j. The amplifier section's output impedance Z_o of the amplifier section may be found by the formula

$$Z_o = \frac{r_p}{1+AB} \quad \text{where}$$

r_p = plate resistance of the final amplifier

B = ratio of input impedance to the feedback impedance

$$B = \frac{Z_{in}}{Z_f + Z_{in}}$$

with some typical values $r_p = 50k\Omega$

positive feedback. According to the type of impedances, and the type of impedance, specific functions such as algebraic summation, multiplication or division by a constant, differentiation, integration and other special function circuits.

The input impedance, Z_{in} , is usually in the 500 k to 1 megohm range. It couples the input voltage from the preceding stage. It is also used as a current summing network to reduce E_{in} to e_g the input voltage to the amplifier section.

The feedback impedance Z_f is also in the 500 k to 10 megohm range. It develops the output voltage E_o and couples the feedback current and voltage from output to input.

operation

The function of the circuit in figure 3 is to reverse the sign of the voltage, and give a gain of -1.

ion

The input voltage E_{in} causes a current I_{in} to flow through Z_{in} .

$$I_{in} = \frac{E_{in}}{Z_{in}}$$

If E_{in} is a positive voltage, then R_a will develop a small positive voltage (e_g) at the input to the amplifier section. The amplifier section will amplify e_g and invert it (odd number of stages) causing a negative output.

The resulting difference of potential between the input terminal and output terminal will cause a current (I_{fb}) to flow through Z_f .

$$I_{fb} = \frac{-E_o}{Z_f}$$

- f. Blocks B through D are the d-c amplifiers. stage gain of only 100 then the over gain of circuit would be $1,000,000 \times 100 = 100 \times 100 = 1,000,000$. Because there is an odd number of stages, phase inversion always occurs.
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$$Z_o = \frac{r_p}{1+AB} \quad \text{where}$$

r_p = plate resistance of the final amplifier

B = ratio of input impedance to the sum of input and feedback impedance

$$B = \frac{Z_{in}}{Z_f + Z_{in}}$$

with some typical values $r_p = 50k\Omega$

impedances, and the type of impedance, specific functions such as algebraic summation, multiplication or division by a constant, differentiation, integration and other special function circuits.

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The resulting difference of potential between the input terminal and output terminal will cause a current to flow through Z_f .

$$I_{fb} = \frac{-E_o}{Z_f}$$

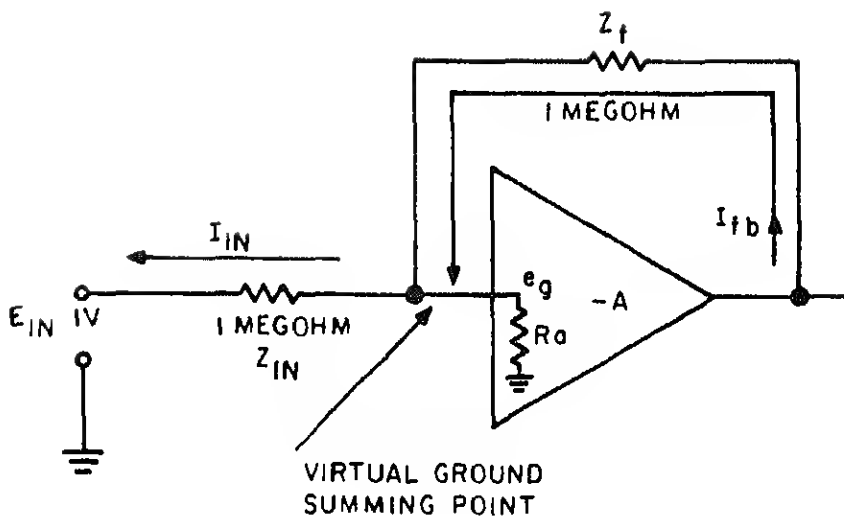


Figure 3

BASIC OPERATIONAL AMPLIFIER OPERATION

$$\text{Gain} = \frac{Z_f}{Z_{in}}$$

$$E_o = \frac{Z_f}{Z_{in}} E_{in}$$

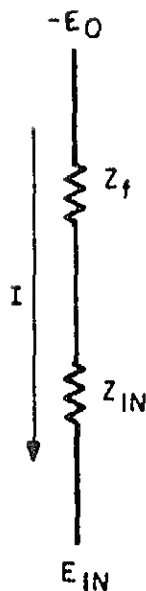
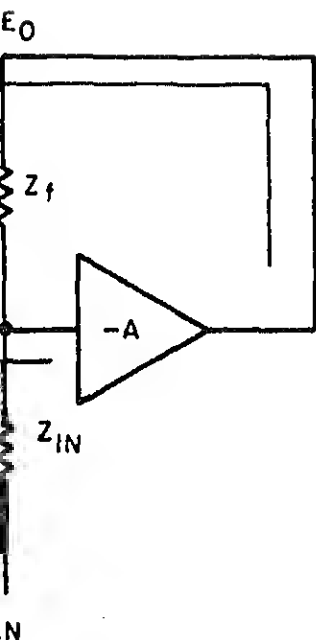


Figure 4

and I_{fb} appear in series and in series circuits currents are equal.

$I_{in} = I_{fb}$, then by algebraic substitution:

$$I_{in} = \frac{E_{in}}{Z_{in}} ; I_{fb} = \frac{-E_O}{Z_f}$$

$$\frac{E_{in}}{Z_{in}} = \frac{-E_O}{Z_f}$$

Solving for E_O ; multiply by $(-Z_f)$.

$$\frac{E_{in}}{Z_{in}} = \frac{+E_O}{Z_f} (+Z_f)$$

$$E_O = \frac{-Z_f}{Z_{in}} E_{in}$$

I_{in}
transposing the formula. The gain of the
amplifier is determined by the ratio of
its circuit configuration and its function
circuit.

- j. In figure 3, then, with an input voltage
 $Z_{in} = 1M$; $Z_f = 1M$. $E_o = \frac{-1M}{1M} 1V = -1V$
 Sign inversion and a gain of negative one
- k. The feedback current (I_{fb}) is determined
 Z_{in} and E_{in} and I_{fb} will equal I_{in} at a
- l. With 1V in and Z_f and Z_{in} both 1 megohm

$$I_{in} = \frac{E_{in}}{Z_{in}}$$

$$I_{in} = \frac{1V}{1M}$$

$$I_{in} = 1\mu A$$

$$I_{fb} \text{ is equal to } \frac{Z_o}{Z_f}$$

$$I_{fb} = \frac{-1V}{1M}$$

$$I_{fb} = 1\mu A$$

$$I_{fb} = I_{in}$$

- m. If Z_{fb} is increased to 2 megohms with
 remaining unchanged, then $E_o = -2V$.

$$I_{fb} = \frac{E_o}{Z_f}$$

$$= \frac{-2V}{2M}$$

2. Multiplication

be performed if the $Z_f:Z_{in}$ ratio is less

1 = division

e_g is very small and may be determined from

in A

e_g is equal to $\frac{E_o}{A}$ where A is the open loop
amplifier section.

as E_{in} and Z_f of 2M and Z_{in} of 1M, then

$\frac{V}{k}$ - open loop gain.

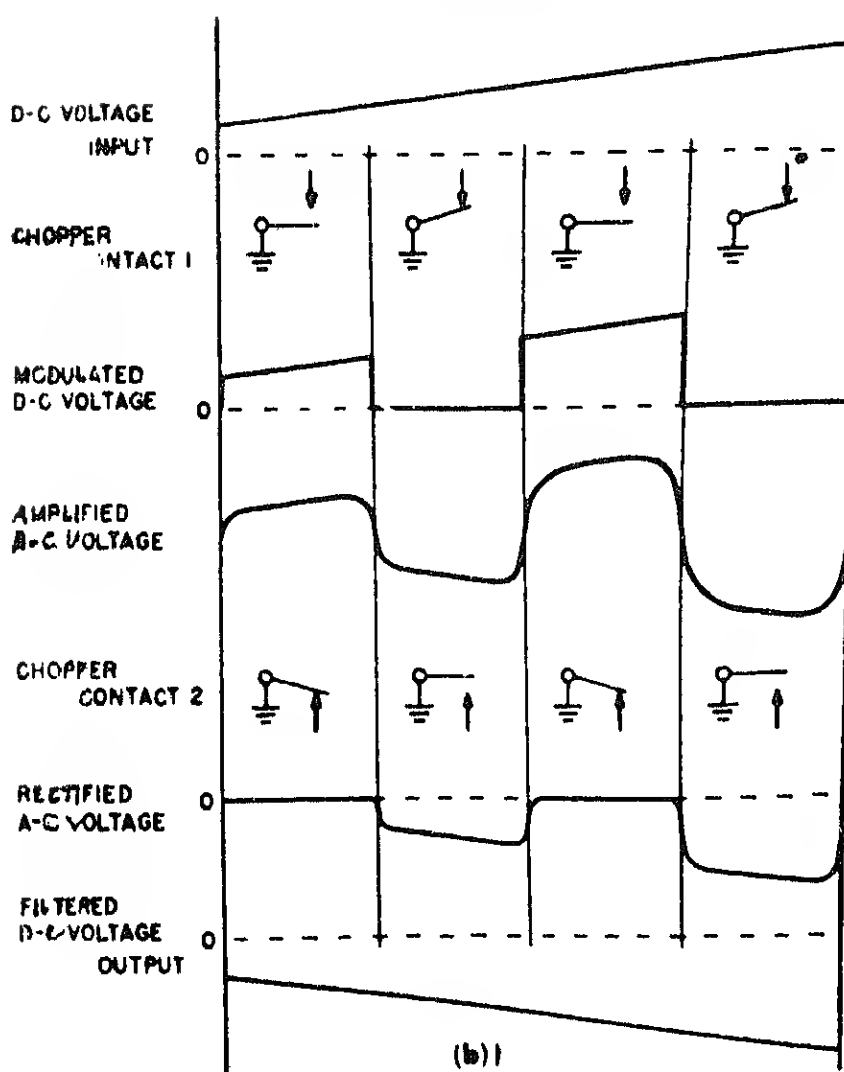
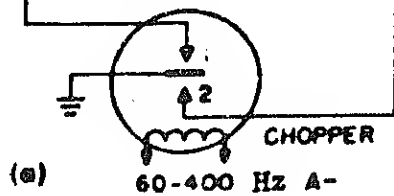
μV

at this point is called virtual ground.
ve impedance is very small. Current flows
point and away from it acting as a ground.

onal amplifier constantly seeks to obtain
l ground. So, when E_{in} increases or
 E_o must correspondingly change, by amplifier
cause a current to flow through Z_f that just
e current flow through Z_{in} .

amplifiers are self regulating. If E_o
due to amplifier gain, component variation,

increases.



The chopper amplifier.

or voltage would be fed back through Z_f and, after processing by the chopper amplifier, would end up as a negative balance signal at the B terminal, reducing the output offset voltage to zero. A similar action occurs for positive drift voltages except that the polarities of the involved signals would be reversed.

To illustrate the properties of high-quality computer amplifiers using chopper stabilization, some representative specifications are tabulated below:

Gain of the d-c amplifier channel, 30,000 to 150,000

Gain of the automatic balancing channel, 2000 to 3000

Total d-c gain, 25×10^6 .

Grid current, less than $10^{-4} \mu\text{A}$.

Average drift over an 8-hour period, 20 to $200 \mu\text{V}$.

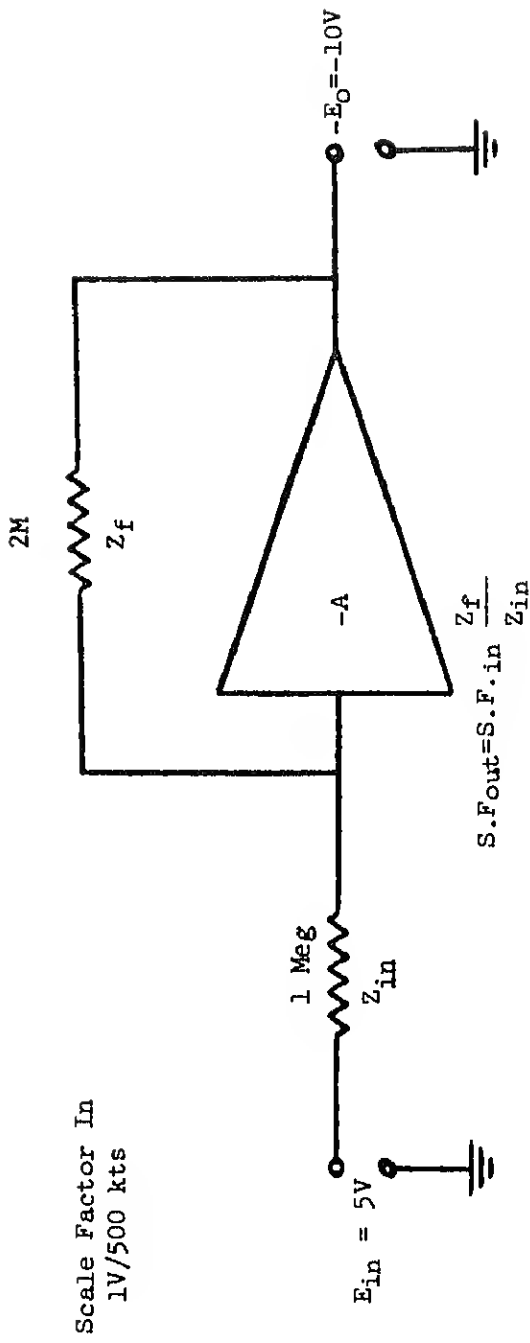
Linear output range, at least ± 100 volts into rated load; decreases above 100 Hz, depending on tube type.

Factors

Input scale factor will be changed by the gain of an amplifier. In an isolation amplifier with a gain of -1, Z_{in} ratio of one, there will be no scale change. There is no change in analog units; therefore, no change in scale factor. If the gain of the circuit is more or less than -1, the scale factor must be changed.

The identity process is used to change scale factors.

If the output voltage is different from the input voltage, then the ratio of analog units to equation units must also change. Refer to figure 7. In figure 7, the Z_f to Z_{in} ratio is -2. With 5V in, E_{out} is -10V. The input voltage represents 2500 knots; therefore, by the law of identity the output voltage must also represent 2500 knots. This means the scale factor must be changed. The output voltage would represent 5000 knots, unless the scale factor is changed.



BASIC SCALE CHANGING OPERATIONAL AMPLIFIERS

Figure 7

$$SF_O = SF_{in} \frac{Z_f}{Z_{in}}$$

$$SF_O = (1V/500 \text{ kts})(\frac{2}{1})$$

$$SF_O = \frac{2}{500}$$

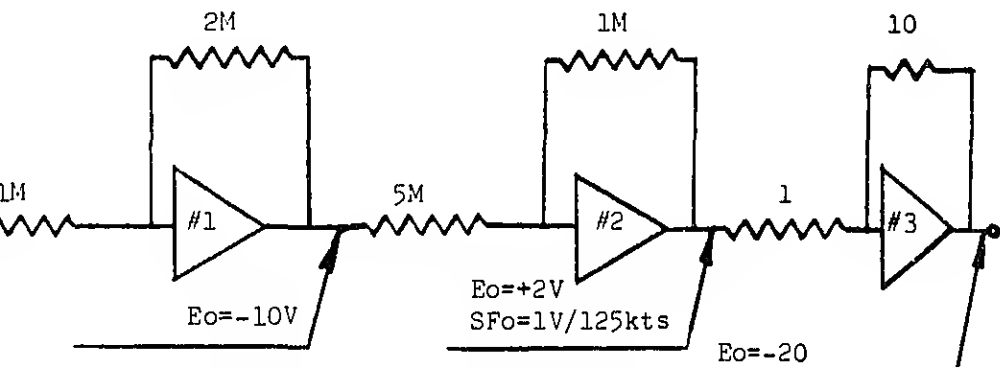
$$SF_O = \frac{1V}{250 \text{ kt}}$$

the new scale factor 1V/250 kts, the output voltage will represent 2500 knots.

$$\begin{aligned} \text{Equation units} &= \text{S.F.} \times \text{analog units} \\ &= (1V/250 \text{ kts})(-10V) \end{aligned}$$

$$2500 \text{ kts out} = 2500 \text{ kts in}$$

In analog devices, input variables must be scaled to represent the same information (equation units) in different modules of the device. This may be accomplished by the circuits shown in figure 8. Note that the input information to amplifier #1, 250 knots of airspeed from the speed circuits is represented by 5V at a scale factor



in

out

Amp #1	5V	1V/50 kts	250 kts	-10V	1V/25 kts
Amp #2	-10V	1V/25 kts	250 kts	+ 2V	1V/125 kts
Amp #3	+2V	1V/125 kts	250 kts	-20V	1V/12.5 kt

Figure 9

H. Basic Operational Amplifier Circuits

1. The circuits covered below are some basic operational amplifier circuits covered in outline form. only basic circuits. There are many more.
2. Summing Amplifiers are used as an electronic circuit. E_O represents the algebraic sum of voltages.

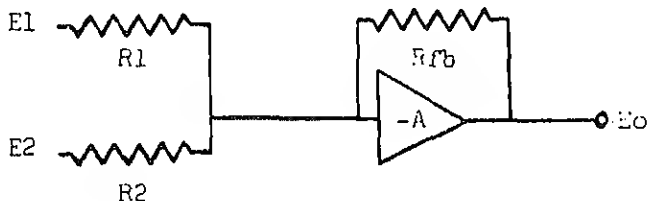


Figure 10

Summing Amplifier

Definition - An operational amplifier with multiple inputs.

3. Operational amplifier switch operates as a switch with its operating point determined by the bias potential.
 - a. With no voltage present on R1 and with E2 voltage, the output voltage will be positive, causing diode CR₁ to conduct.
 - b. Resistance of CR₁ when conducting is very low.
 - c. Output voltage would be near zero.

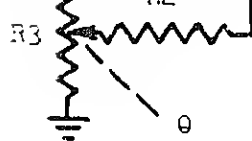


Figure 11

Operational Amplifier Switch

1 that resistance of conducting diode is about ohms.

$$E_o = \frac{-Z_f}{Z_{in}} E_{in}$$

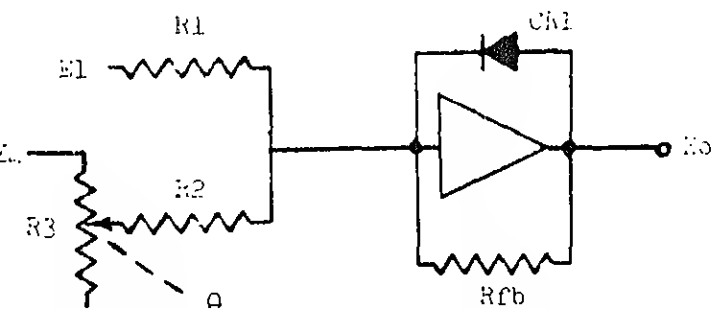
$$E_o = \frac{-100}{1M} E_{in}$$

E_o is very small

input potential on R_1 becomes sufficiently
ive to drive input to a positive voltage E_o will
e negative and diode CR_1 becomes reversed biased.

Feedback impedance increases and gain switches from
o high.

specific gain is desired, a resistor is placed in
lel with the diode.



4. Logarithmic amplifier

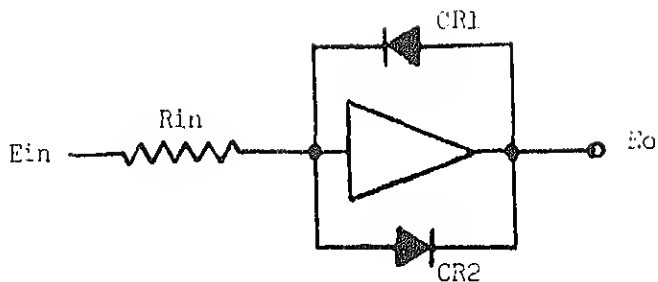


Figure 13

Logarithmic Amplifier

- a. Diodes CR_1 and CR_2 are special function diodes with variable conduction level.
- b. Two diodes are used so that there may be both positive and negative inputs.
- c. As input voltage increases in amplitude, one diode conducts more, the other, depending on the polarity of the input, conducts less.
 - (1) As diode conducts harder, current flow increases.
 - (2) It seems as if Z_f had decreased.
- d. This results in a logarithmic gain for this amplifier.
 - (1) High gain for small signals because of low conduction, therefore high resistance of diodes.
 - (2) Low gain for larger signals.

Figure 14

Integrating Amplifier

ates input voltage with respect to time by
lating charge on capacitor.

ample, if an input voltage waveform represented
ration, the output voltage would be the integral
eleration, i.e. velocity.

Integrating Amplifier

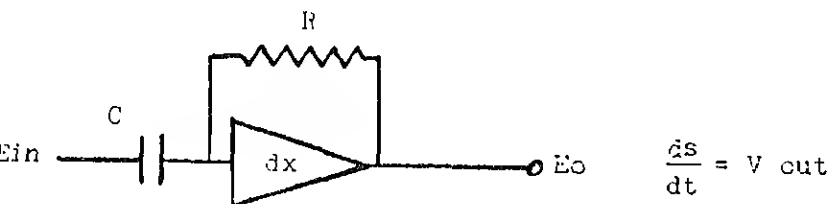


Figure 15

Differentiating Amplifier

entiates input voltage.

voltage represents derivative of input.

ample, if the input voltage represented displace-
then the output would represent ds/dt or V .

c Circuits, NAVSEA 0967-LP-000-0120, pages 5-279 to

r and Integrated Electronics, Kiver, M. S.,
ll, Fourth Edition, 1972, pages 306 to 310.

d Circuits and Semiconductor Devices, Deboo and
McGraw Hill, Second Edition, 1977, Chapter 4.

cs Communication, Schrader, R. L., McGraw Hill,
ition, 1980, pages 216 and 317.

TLINE:

t-Coupled Amplifiers

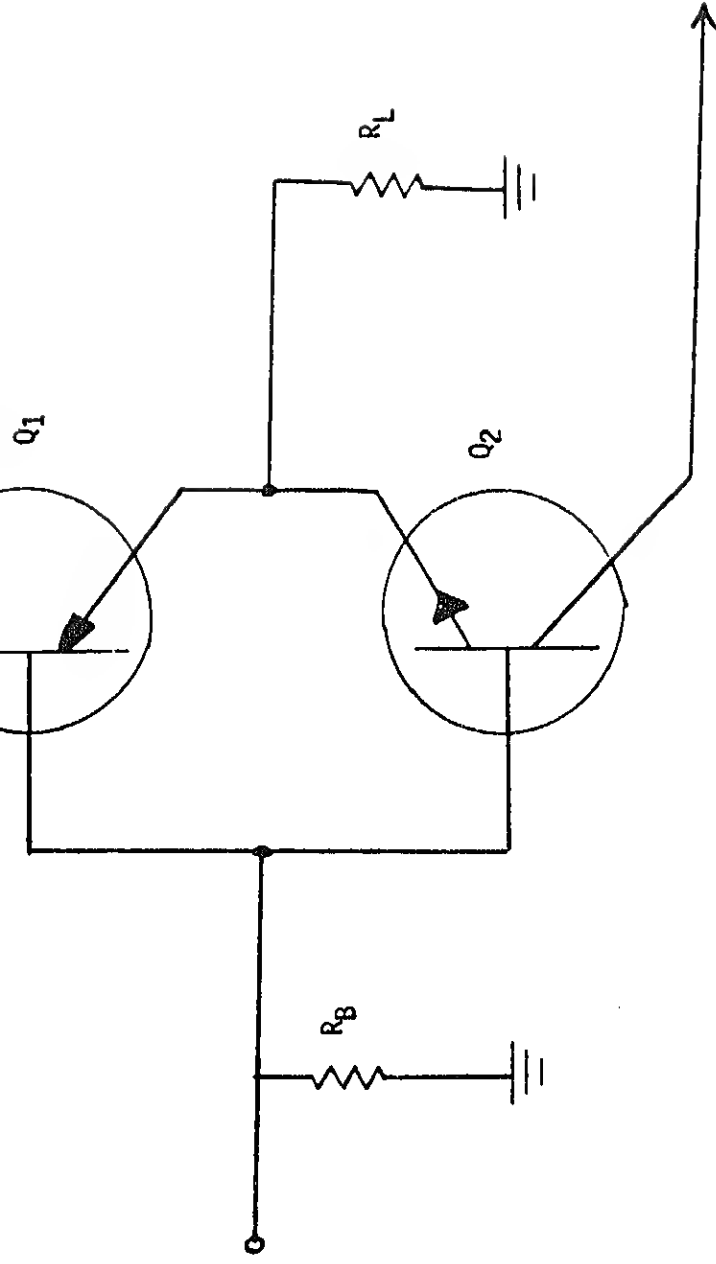


Figure 1 - Complementary Symmetry

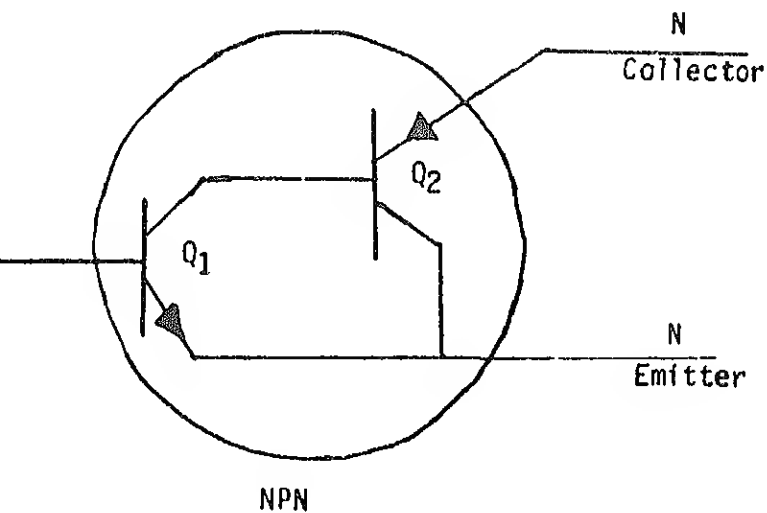
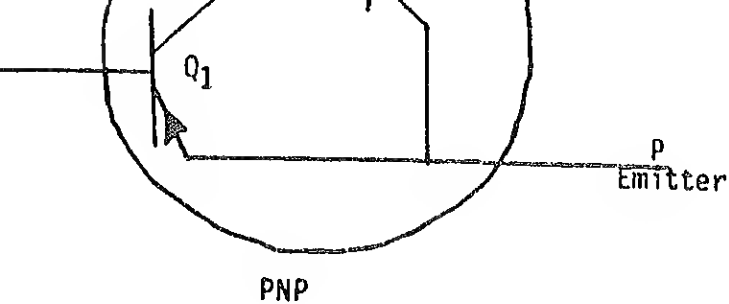
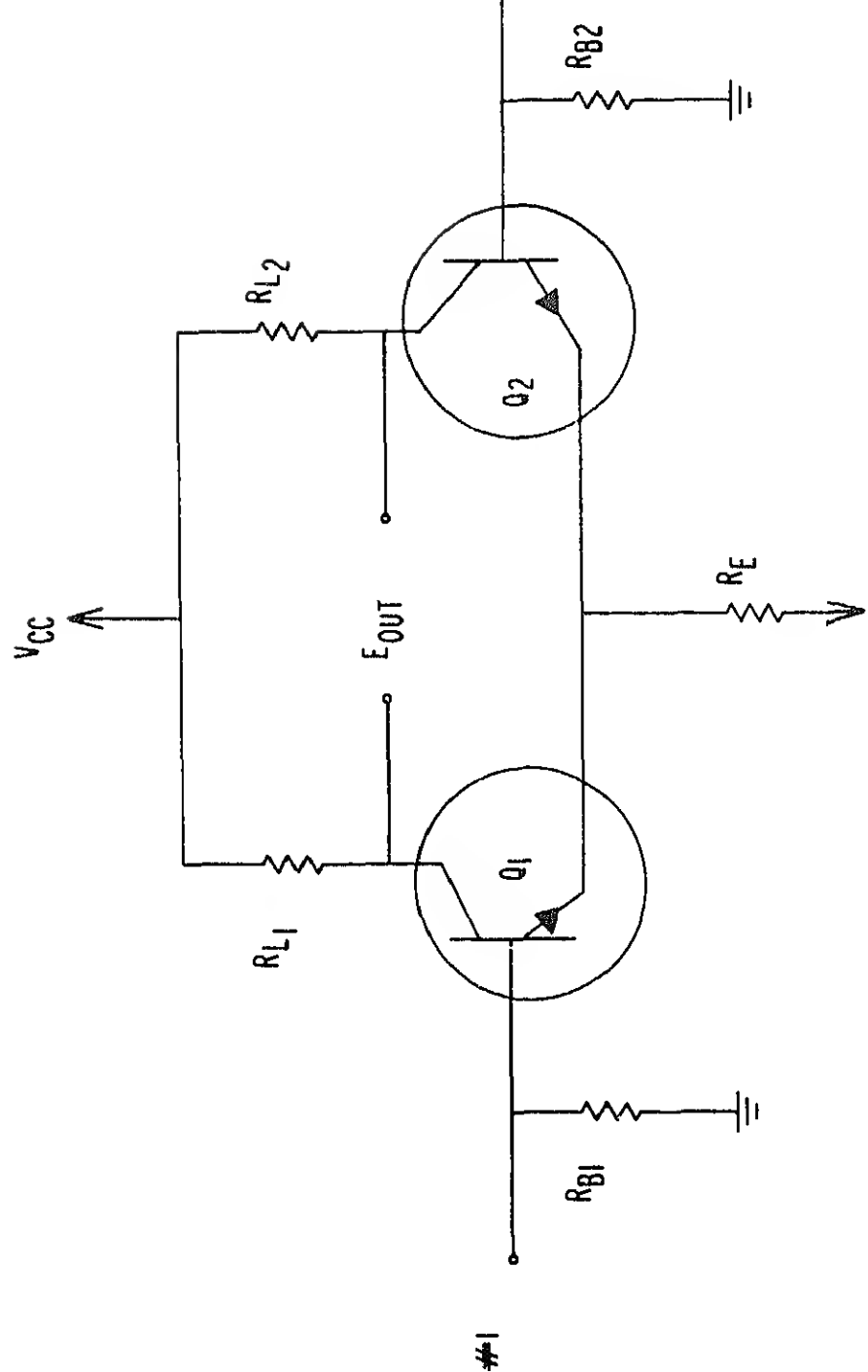
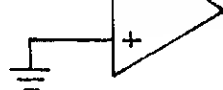


Figure 2.-Complementary Darlingtontons.

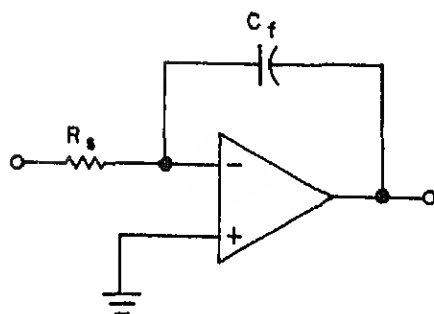




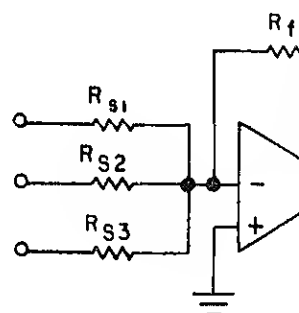
(a)



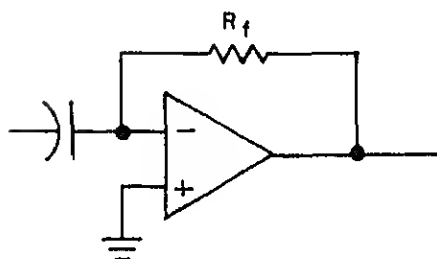
(b)



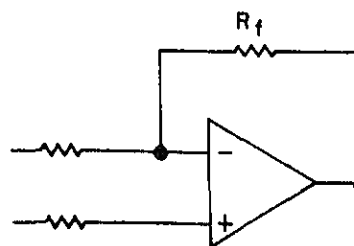
(c)



(d)



(e)

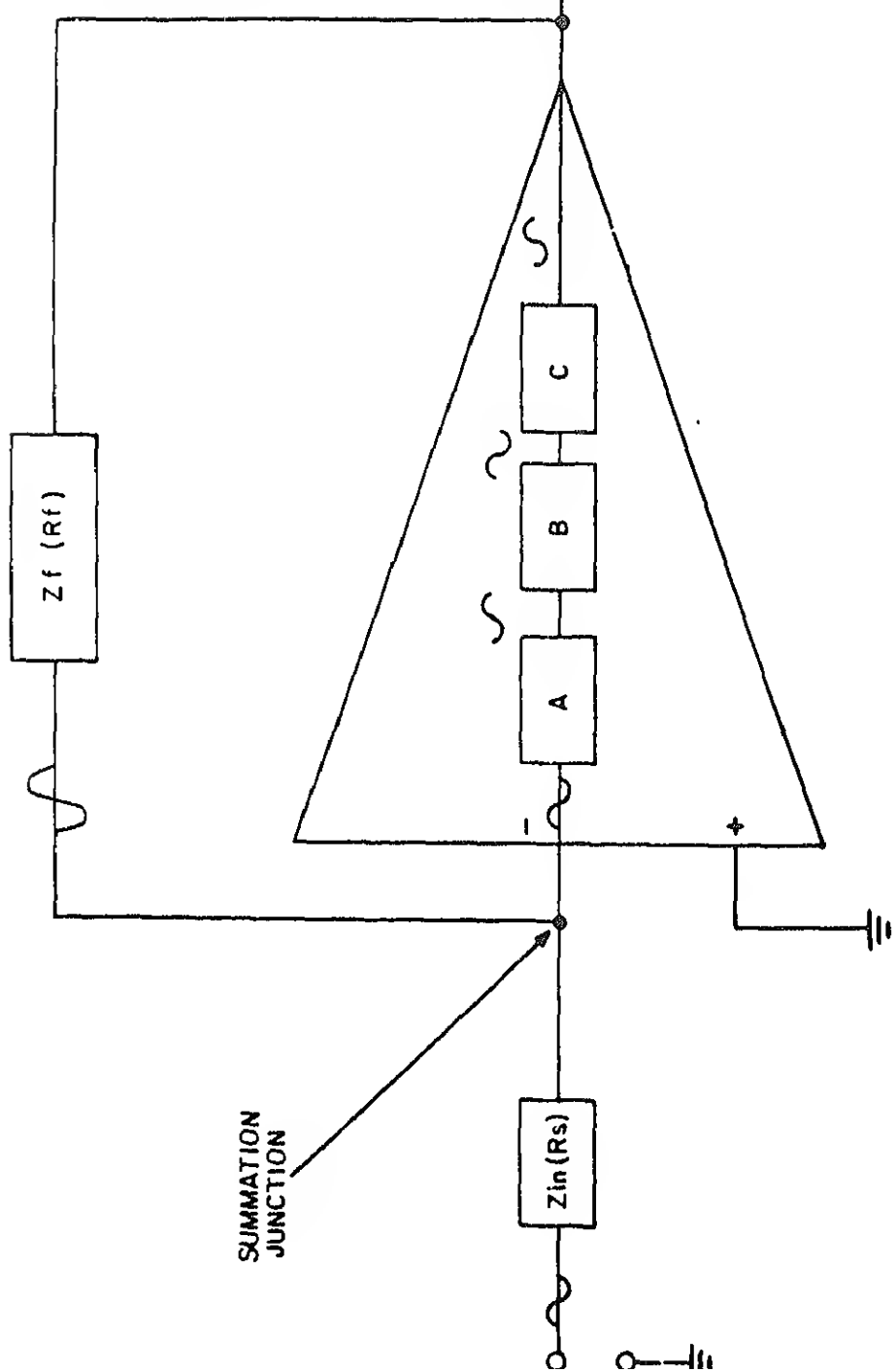


(f)

Figure 4 -Operati 1 Amplifier

atic symbol

functional analysis



al amplifier

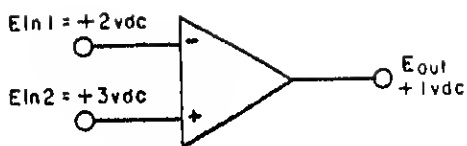
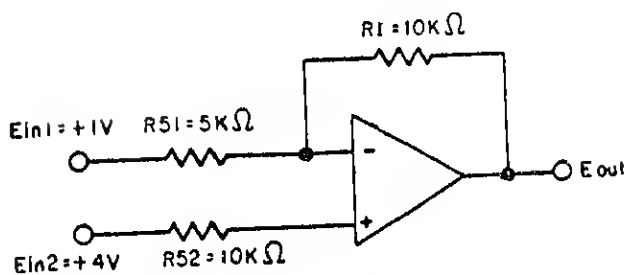


Fig. 3 DIFFERENTIAL AMPLIFIER (basic)

Figure 6

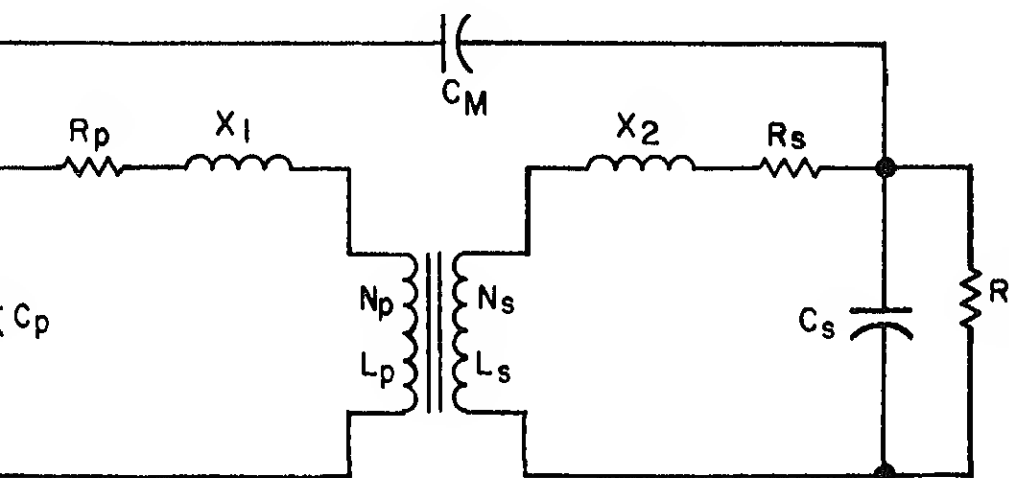
nce ratio



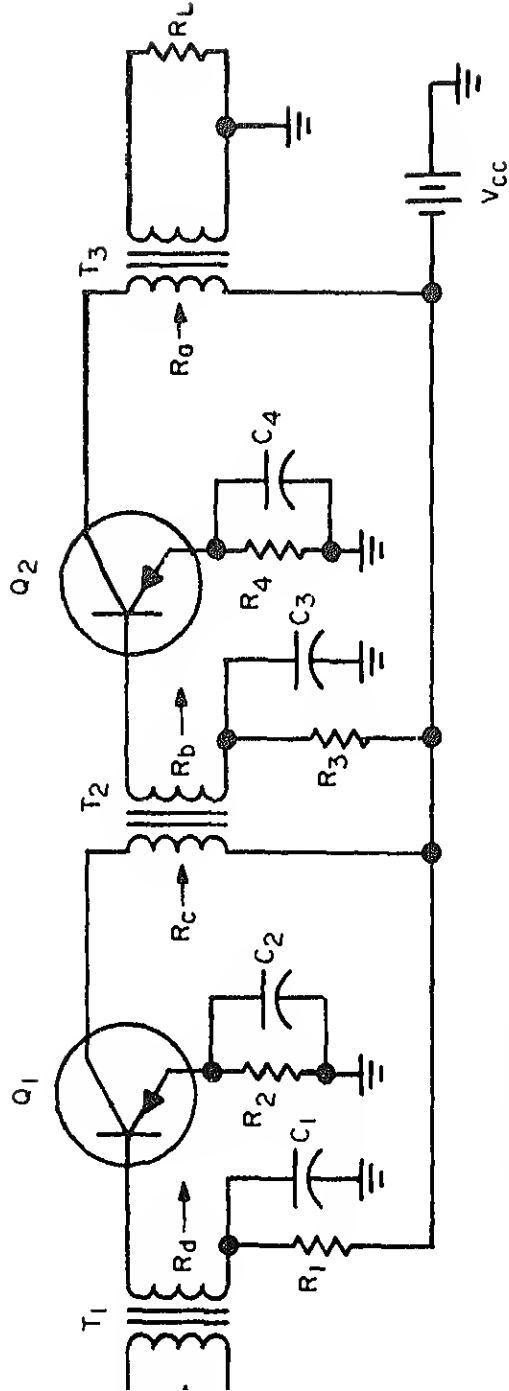
onic systems, ranging from voltage regulators to computation systems, require the amplification of d-c and a-c signals. Many times one stage of amplification is not sufficient to amplify the amplitude of such signals to the required values; therefore, the different types of coupling are necessary to ensure the transference of energy is required. This lesson on transformer coupling is essential for the technician.

S. Kiver, Transistor and Integrated Electronics. McGraw-Hill Book Company, Fourth Edition, 1972.

L. Shrader, Electronic Communication, McGraw-Hill Book Company, Fourth Edition, 1980.



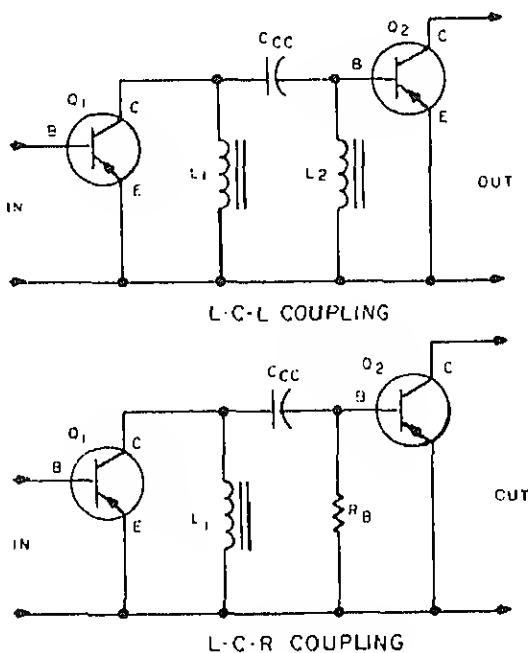
TRANSFORMER EQUIVALENT CIRCUIT



TRANSFORMER-COUPLED TRANSISTOR AMPLIFIER

Figure 2

or an inductor provide more output than the load resistor. While the overall frequency response of impedance coupling is not as good as that of resistance coupling, it is much better than that of transformer coupling, because there are no leakage reactance effects to deteriorate the high-frequency response. The high-frequency response of the impedance coupler is limited mainly by the collector output capacitance, and the low-frequency response is limited by the shunt reactance of the inductor, L_1 . The efficiency of the impedance coupler is approximately the same as that of the transformer-coupled circuit (50% for the ideal case). See figure 3.



Impedance-Coupling Circuits

Figure 3

2. Transformer coupling--Transformer coupling is used extensively in cascaded transistor stages and power output stages. It provides good frequency response and proper matching of input and output impedance.

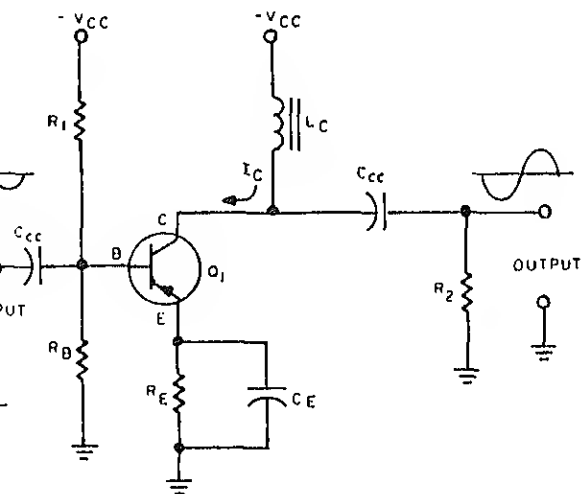
3. Coupling between stages is achieved through inductive coupling of primary and secondary windings. Since these windings are separated physically, input and output circuits are isolated from each other yet coupled for a-c signal transfer. The primary winding presents a low d-c resistance, minimizing collector current losses and allowing a low collector voltage for the same gain as other coupling methods, and it presents an a-c load impedance to the following stage. The secondary winding is connected to the base d-c return path and provides better stability because of the low d-c (winding) resistance. Since the transistor input and output impedances are matched by using the proper turns ratio, maximum available gain can be obtained from the transistor.
4. As in the impedance coupler, the shunt primary transformer windings causes the low-frequency response to drop off, while high-frequency response is limited by the leakage reactance between the primary and secondary windings, in addition to the emitter capacitor and collector capacitance. Because of the low d-c resistance in the primary winding, no excess power is dissipated and the power efficiency approaches the theoretical value of 50%.

B. Transistor impedance-coupled audio amplifier

1. Application--The impedance-coupled transistor amplifier is used where higher gain than common-emitter stage is desired with better response than provided by transformer coupling.
2. Characteristics
 - a. Uses common-emitter circuit for high gain.
 - b. Operates class A for linear operation with low distortion.
 - c. Usually amplifies small signals, but can be designed to handle large signals in class AB or class B.
 - d. Is fixed-biased from the collector supply.

Impedance-coupled transistor amplifier is similar in a general sense to the impedance-coupled iron-tube amplifier.

Figure 4 shows a conventional PNP, triode, common-emitter impedance-coupled transistor audio amplifier circuit.



Impedance-Coupled Audio Amplifier

Figure 4

The input is shown capacitively coupled, and voltage divider R_1 , R_B provides fixed bias from the collector supply. Emitter swamping is provided by temperature stabilization; R_E is bypassed by C_E . Collector impedance L_C is the load across which the output voltage is developed; this voltage is applied through coupling capacitor C_{CC} to the input circuit. Resistor R_2 is the base-to-ground resistor in the next stage when cascaded amplifiers are used, or is the output load resistor (such as a speaker) in a single-ended stage. (In some applications, R_2 may be replaced by an iron-cored inductor similar to L_C .)

developed across R_B ; this bias is sufficient to cause the quiescent value of I_C to be small, although the collector is reverse-biased.

d. When the input signal goes positive, the forward base bias is increased instantaneously by the amplitude of the input signal, and collector current I_C is increased. This increase in collector current causes a reduction in collector current across collector impedance L_C to develop a voltage drop toward the supply voltage, which is a negative-swinging output signal. When the input signal becomes negative, the forward base bias is reduced and causes I_C to decrease. The increase in collector current then produces a large voltage drop across the collector impedance, which reduces the negative collector voltage and produces a positive swing. Therefore, the output follows the input signal except it is reversed in polarity; when the input is positive, the output signal is negative, and vice versa. The collector output is developed across the impedance of L_C between the collector and ground, and is applied through coupling capacitor C_{CC} to the base of the next stage, or to a load.

e. In cascaded impedance-coupled stages, the collector resistor and base-to-emitter internal resistance of the next stage transistor offer a shunt path to ground between coupling capacitor C_{CC} and ground. Therefore, the reactance of C_{CC} and the transistor resistance (or impedance) from the collector of the first stage. If the reactance of the coupling capacitor is large, the output voltage is attenuated, and only a small output voltage is developed across the base and ground of the second stage. The reactance of C_{CC} varies inversely with frequency; the lower audio frequencies are attenuated more than the higher frequencies. For good frequency response, the coupling capacitor must be sufficiently large in value that its reactance is very small as compared with the base resistance or impedance. This is similar to vacuum-tube practice, where relative

capacitor should always be less than one-tenth the effective base input impedance.

In those circuits where an impedance replaces R_2 , the coupling capacitor and inductor can be made to series-resonate at a low frequency to provide base boost. At the higher audio frequencies (about 15,000 Hz), the collector-to-emitter shunting capacitance of the second stage, together with the large distributed capacitance from turn to turn of the collector-inductance, tend to bypass the high frequencies to ground, causing a drop in the response.

The frequency-attenuating action produced by the transistor occurs because the width of the internal transistor PN junctions is voltage-sensitive. With higher voltage, the transition region is narrow, corresponding to the closely spaced plates of a capacitor with the associated high capacitance. The reverse bias on the collector also reduces the width of this transition region, so that transistors are generally characterized by a high inter-electrode capacitance. For example, an audio transistor may have a collector-to-base capacitance on the order of 50pF, as compared with a vacuum-tube plate-to-grid capacitance of one or more pF. The collector-to-emitter capacitance is usually 5 to 10 times the value of the collector-to-base capacitance (in the common-emitter circuit), as compared with 8pF or less for vacuum-tube plate-to-cathode capacitance. Thus, it can be seen how the high-frequency response is affected considerably by internal transistor parameters. Of course, any shunt wiring capacitance and that of the collector inductance will also add to the shunting effects of the transistor. Both low-and high-frequency compensating circuits may be used to increase the frequency response of the circuit.

Over the region of 100 to 15,000 Hz, the impedance coupled amplifier has a relatively flat response, and with proper matching will afford high power and voltage gains. Hence, this form of coupling is

i. Transistor amplifiers are also by a high inherent noise which is greater at lower audio frequencies. Operating at low emitter current and low collector current together with low values of input resistance to minimize the noise. By using an emitter resistor (instead of the base-to-ground resistor in the schematic), a very low input resistance and lower noise figure over that of the common-emitter amplifier, is obtained. In the common-emitter amplifier, degenerative effects produced by an emitter resistor tend to increase the input resistance. Thus, it is conventional to use large emitter bypass capacitors to avoid the possibility of degeneration. As with vacuum tubes, external feedback circuits provide better response, although emitter degeneration can be used. Since fixed bias from a collector supply may be easily obtained by a voltage divider, it is used in both large-signal and small-signal applications. Self-bias is generally used in very small-signal amplifiers; however, distortion and improper operation will result in gain, or blocking, may occur on load. The emitter resistor functions mainly as an emitter resistor for temperature stabilization and prevents large changes in amplification with temperature variations.

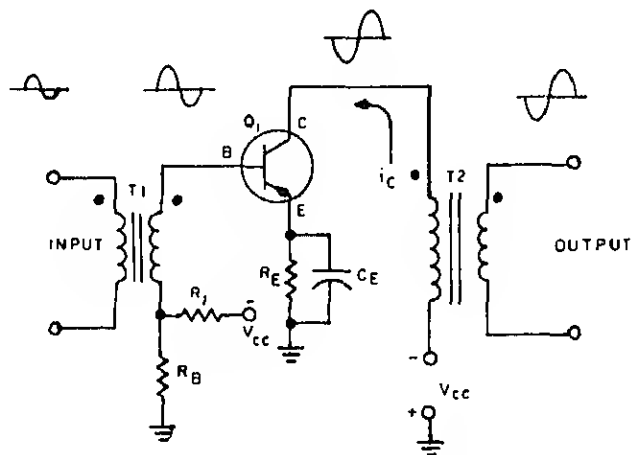
j. In considering the operation of the transistor impedance-coupled amplifier as compared to an electron-tube impedance-coupled amplifier, it should be clear from the above discussion that the transistor circuit is an almost exact counterpart of the other. The difference is that the transistor stages operate with low input and output impedances, at low voltages, and at very low power amplification, whereas electron-tube stages operate with relatively high input and output impedances, at high voltages, and at high levels of amplification. Thus, the transistor is basically a voltage amplifier, while the electron tube is a power amplifier. Consequently, the transistor requires closer matching (rather than mismatch) of input and output impedances to maximize performance.

Characteristics

- a. Uses common-emitter circuit for higher gain.
- b. Operates class A for linear operation and minimize distortion.
- c. Usually amplifies small signals, but can be designed to handle large signals in cascaded stages.
- d. Is fixed-biased from the collector supply, but may use self-bias in some applications.
- e. Emitter swamping is normally used for thermal stabilization.
- f. Gain is fairly uniform over a range of approximately 100 to 10,000 Hz or more.
- g. Both voltage and power gains are high.

Circuit analysis

- a. The transformer-coupled transistor amplifier is similar in general to the transformer-coupled electron-tube amplifier. See figure 5.



ization; R_E is bypassed by C_E . The output is transformer-coupled through T2.

- c. The use of T1 to apply the input signal to the base circuit provides an almost ideal temperature-stable response characteristic. The low transformer impedance produces a low base input resistance, and when used with emitter swamping resistance, the variation in gain with temperature is a very small value over a large range of temperatures (greater than for any other type of common-emitter circuit). Normally, transistor Q_1 rests in its quiescent condition, with class A biasing provided by voltage divider R_1, R_2 . The quiescent collector current, I_C , is steady, producing only a constant voltage drop across the primary of T2. Thus, practically the full collector supply, V_{CC} , is available. With a steady collector current, no voltage is induced in the secondary of T2, and there is no output signal (input signal or noise). When a positive input signal is introduced into the input circuit, the flow through the primary of T1 induces a voltage in the secondary, which is applied to the base of Q_1 . Assuming that the transformer secondary is in-phase with the primary, a positive voltage appears at the base. This positive swing cancels the forward negative bias, and the induced flow of collector current occurs. When the instantaneous collector current decreases, the primary voltage drop also decreases, and the collector voltage to rise toward the V_{CC} value. Meanwhile, the reducing collector current induces a voltage in the secondary winding. Since the secondary winding is connected in-phase with the primary, the reducing collector current produces a positive voltage swing in the secondary, and an increase in collector current produces a positive swing. The collector current flowing through R_E is the steady-state value, and any change in base bias with the input signal is bypassed around the emitter resistance by capacitor C_E . Although the capacitor passes the quiescent d-c current, it will pass the varying audio voltage produced by the input signal. Thus, only d-c current change

the forward bias and hence reduces the collector current back to the original value so that it appears unchanged. If the emitter bypass capacitor were not used, the input signal voltage would produce a degenerative effect, since all collector and emitter current would be forced to flow through the emitter resistor.

Consider next the next negative swing of the input signal. In this instance, the forward bias on the base element is increased (the two negative voltage add), and a heavy collector current flow occurs. The increasing I_C through the primary of T2 induces a voltage into the secondary. Assuming the same in phase connection of the primary and secondary, the output voltage is positive. By changing the connections of the secondary winding of either T1 or T2, the signal can be changed so that it is of the same phase at both the input and the output; this is an advantage of transformer coupling.

Since the secondaries of T1 and T2 are not connected to their primaries, the transformers offer a convenient method of separating input or output signal from bias or collector voltages. By using the proper turns ratio, the primary and secondary impedances may be matched. In the base circuit, the input resistance is matched, giving maximum gain; likewise, in the output circuit, the proper turns ratio reflects the secondary load impedance into the primary, which, when added to that of the transformer primary itself, provides a matched load for maximum output.

Normally, the transformer-coupled stage is operated in the middle of its transfer characteristic to produce linear amplification. It is also a small-signal amplifier when used in preamplifier stages. In following cascaded stages, it becomes a large-signal amplifier, operating with a larger bias over the linear range of its transfer characteristic. When necessary, bias resistor R_B is bypassed to ground with a large capacitor to prevent audio signal voltages from causing the bias to change with the signal, particularly in high-gain and large-

stages, the flow of reverse (leakage) current through the collector-to-base junction is important when it is a large percentage of the operating collector current. Thus, the designer chooses a transistor with as large a β as possible, and as small a leakage current as can be obtained, in order to get the most gain for the least leakage current. (The flow of reverse current does not occur in electron tubes.)

- h. The frequency response of the transformer-coupled amplifier is lower than that of the resistor- or impedance-coupled transistor audio amplifier. There is more shunting capacitance than in the resistor coupling because of the transformer's distributed turn capacitance, and there is more inductance between the primary and secondary windings. It does not exist in the impedance-coupled amplifier. The primary inductance is usually made from the load resistance, R_L , for good low-frequency response. However, the lower the frequency, the higher the inductive reactance, so that the response tends to drop at low frequencies. The high-frequency response is primarily determined by the effect of shunting capacitance with load resistance. The linkage inductance, while the low-frequency response is determined by the combination of load resistance and magnetizing inductance. In addition, the shunting capacitance and inductance for the transformer circuits which produce humps in the response curve. Practically speaking, the response is worse than that of the electron-tube transformer-coupled audio stage, with somewhat less high-frequency response. Loss of low-frequency response is more apparent when miniaturized transformers are used because of the difficulty of building transformers with a sufficiently large iron core to provide high inductance with the limited number of turns available in the space allocated.

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Book Company, Fourth Edition, 1972.

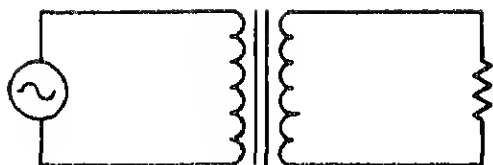
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Instruction, Transformers, M135.

LINE

ges/Disadvantages

former Theory



$E_p = 440V$
 $N_p = 600$
 $E_s = 110V$
 $I_s = 5a$

Figure 1

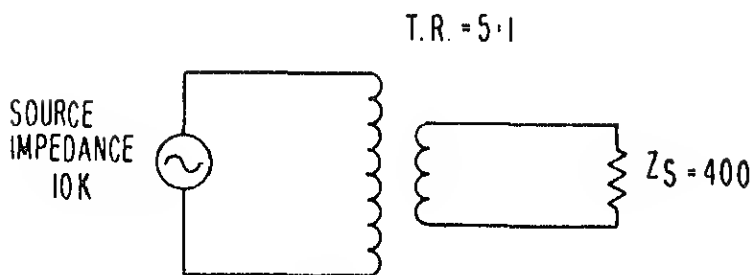


Figure 2

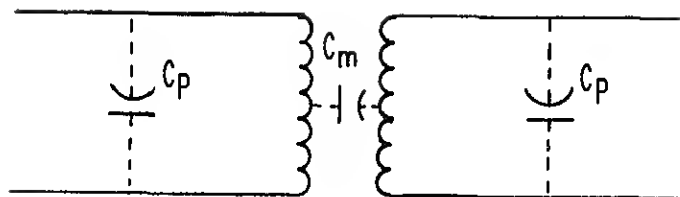


Figure 3.- Distributed Capacitances in Transformer

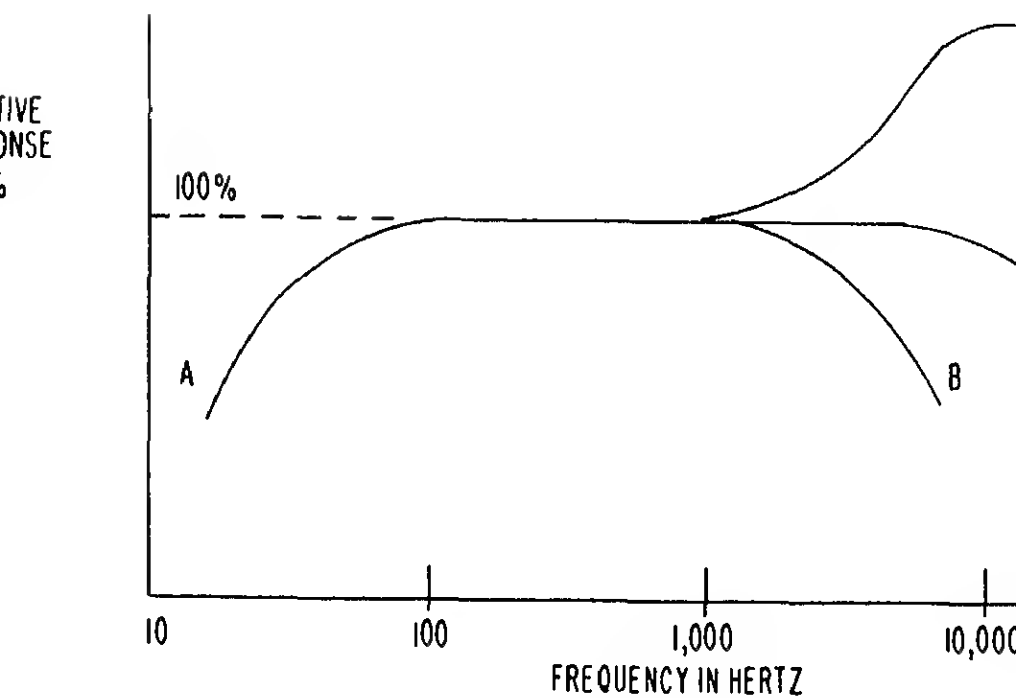


Figure 4.- Frequency Response of Transformer

ION

e the development of solid state devices, the ability to amplify or control has been under constant investment. Manufacturers have been forming layers of semiconductor, inserting PN junctions, shaping new geometries, and pushing levels in the search for new control or amplification. Some of the newly made special devices parallel transistor characteristics; while other devices completely take over what a transistor cannot perform. At the present state-of-the-art, several devices will be explained in this chapter.

S

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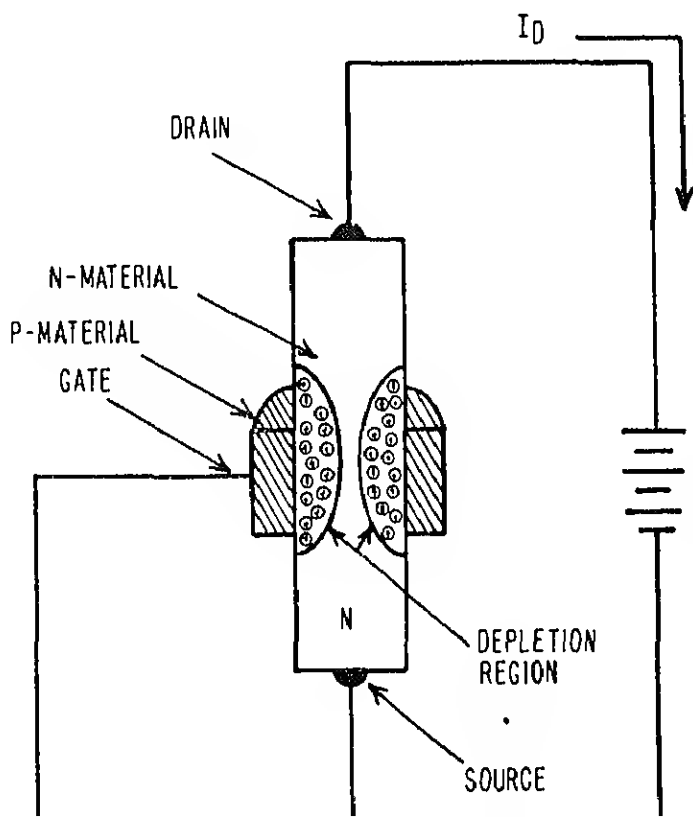
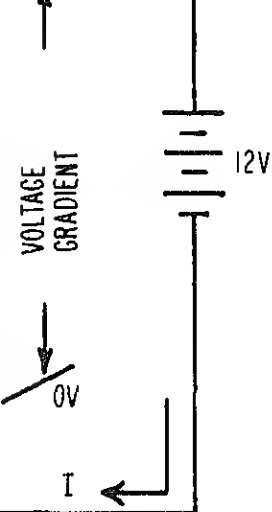
CONSTRUCTION AND OPERATION OF JFET

JFET Construction

1. The Junction Field-Effect Transistor (JFET) is a solid state device with a very high input impedance and high output impedance--two favorable attributes also found in vacuum tubes. Like a vacuum tube, the JFET is a voltage-controlled device. (The conventional transistor is a current-controlled device.) In its operation and construction, the JFET is completely different from a vacuum tube, yet many circuits of both are similar. The JFET is a semiconductor device with no filament, so no excess heat must be dissipated. It can be operated at high voltages comparable to those of small vacuum tubes, or with the low voltages normally used in solid state devices.

tors. They also are used in small-signal video amplifiers. A few high-power junction effect transistors are available with high capabilities. As the demand rises and production techniques improve, higher power JFETs will be marketed.

4. Like most solid-state devices, field effect transistors are temperature sensitive, but not as much as bipolar transistors. Input and output impedances of the FET are moderate. Both thermal and capacitance problems are reduced when appropriate external circuit designs are used. JFETs are destroyed quickly if maximum ratings are exceeded. In the production of many solid-state devices, wide variations in units of the same performance specifications are not too strict a limitation also can be compensated for by external circuit design.
5. The simplified JFET structure shown in figure 1A is helpful in obtaining a fundamental understanding of JFET operation. First imagine a simple bar of semiconductor material with direct (ohmic) contacts at each end. Excess electrons are available in the material when a voltage source connected across the leads causes the movement of electrons. The magnitude of the current flow depends on the applied voltage, the doping, and the dimensions of the semiconductor bar. Of course, the larger the cross-sectional area of the bar, the lower the resistivity. Likewise, the heavier the doping of the N-type material, the lower the resistivity.
6. It is not feasible to vary the physical dimensions of the bar or its doping level; however, it is possible to influence the movement of charges by changing the resistivity of the bar. This can be done by varying the depletion region.
7. The connection of a voltage source between the gates (figure 1A) sets up a voltage gradient across the semiconductor material. The voltage at a point becomes more positive as one proceeds along the bar from the negative gate to the positive gate.

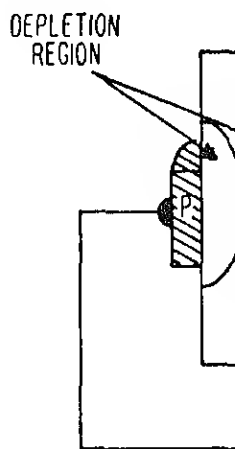
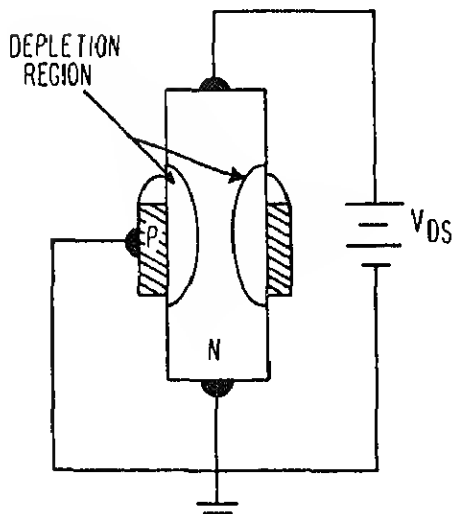


reverse bias on the junction is obtained positive gradient that extends from the the bar to the positive end.

9. In previous lessons, the influences of a on the depletion regions associated with were detailed. It is this activity that control the movement of charges through JFET terminology the bar is called a channel, therefore, figure 1(B) is an N-channel JFET). that controls the motion of charges along is called the gate. The common end of t its associated lead is known as the source opposite end of the channel and its asso called the drain. The gate can be compa control grid of a vacuum-tube--the source be compared to the cathode and plate res.

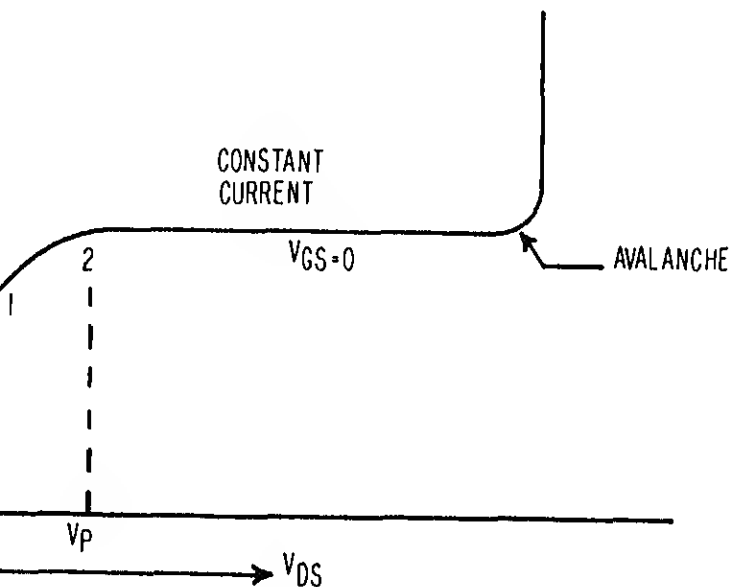
B. Influence of the Reverse-Biased Junction

1. A reverse-biased junction causes the dev depletion region in the channel, as show Adequate doping keeps the resistivity of material lower than that of the channel



ce of the depletion region in the channel increase in the resistivity of the bar. If source voltage (V_{DS}) is increased, the region extends farther into the channel, its resistance. In figure 2(B) the region would seem to extend through the such a manner that channel current would be "pinched off."

however, counteracting influences that pre-omplete pinch-off of the current. Increasing to increase the current, while a larger depletion tends to reduce it; thus, current is not. The combined influence of the depletion the voltage drop establishes a condition in current rises to a maximum and then holds a further increase in channel current with an (V_{DS}). This is indicated by the curve in

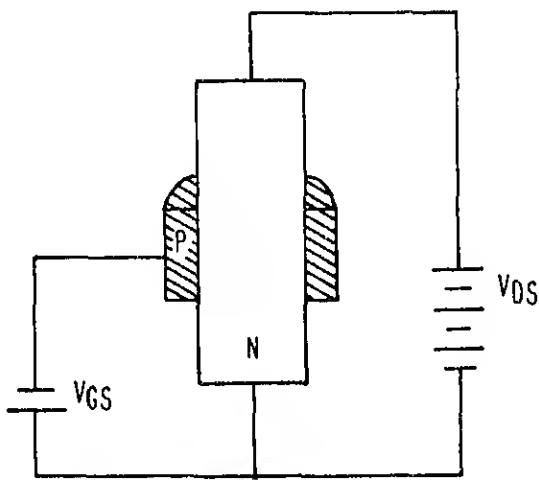


Point 2 corresponds to full penetration of the depletion regions (where the two depletion regions meet). This is the pinch-off condition. Operation now is in the saturation current region where the drain current remains at the same level despite the increase in V_{DS} .

5. If the drain-source voltage is made too large, the channel junction will undergo avalanche breakdown, causing the current to rise sharply. It is important that the device will be damaged if power dissipation is not held to a safe level.

C. Influence of the Gate Potential

1. The resistivity of the channel depends on the drain voltage and gate voltage. The influence of the gate on the channel current can be enhanced by connecting a negative voltage between the gate and source (common), as shown in figure 4. This establishes a larger depletion region and increases the channel resistivity for a given V_{DS} . In other words, it will cause pinch-off at a lower V_{DS} . Thus, the limiting drain current will also be lower. If the gate bias voltage is made high enough, the drain current can be reduced practically to zero. This activity can be compared with the cut-off region of a tube's plate current when a high control grid voltage is applied.



There are three main regions. In the ohmic region the drain current rises significantly with the increase in the drain-source voltage because neither gate potential nor the channel IR drop have enough influence to cause pinch-off. The drain-source voltage has a significant influence on the drain current, and the output resistance is relatively low. The second region (pinch-off) is one of saturation. The current remains essentially constant for a large change in V_{DS} . This constant current characteristic means that the output resistance is high, providing favorable operating conditions when high voltage and/or power gain are desired. The third region is the breakdown (avalanche) region.

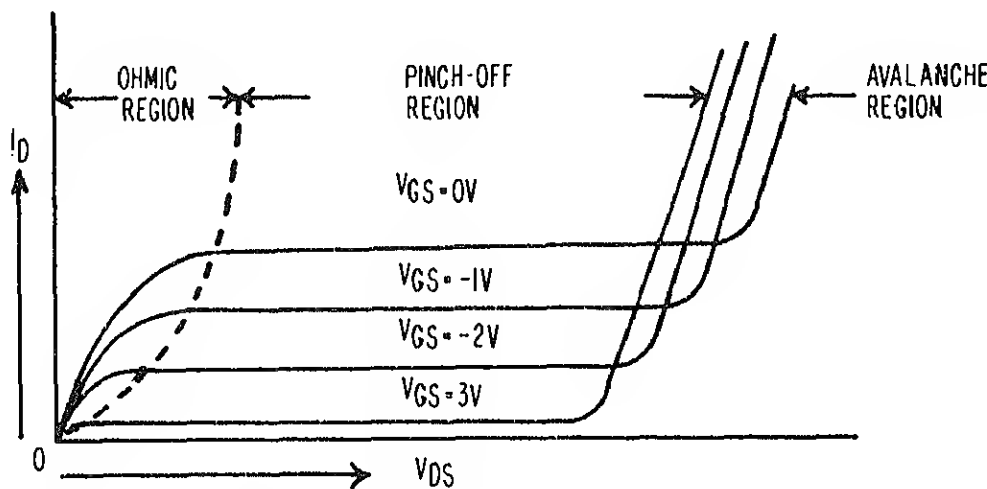


Figure 5 Family of Curves for a Typical N-Channel JFET

As long as the gate-channel junction is reverse biased

There will be corresponding changes in the of the channel and the movement of charges channel. Consequently, the drain current the changes in the gate-source voltage (V_G control of the channel current (I_D) by V_{GS} the influence that a grid voltage has on t the electrons (plate current) between the the plate of a vacuum tube. To the extent signal voltage across a high impedance con output current, a field-effect transistor a vacuum tube than a bipolar transistor.

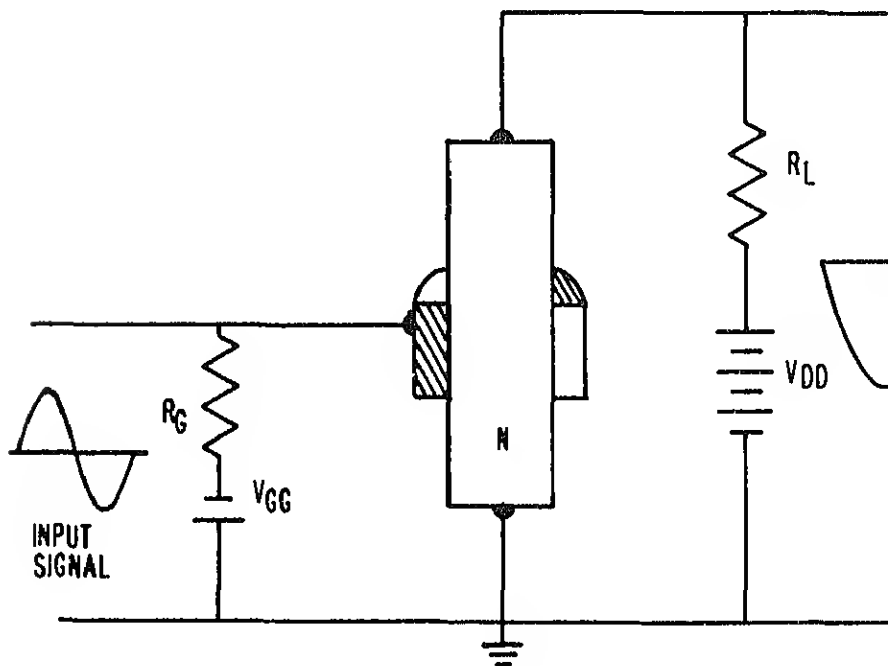
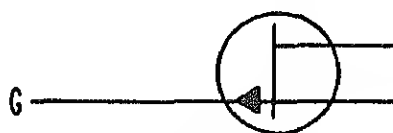
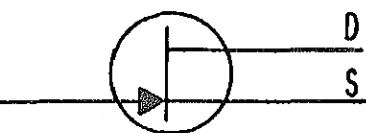
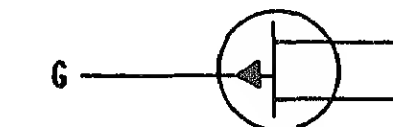
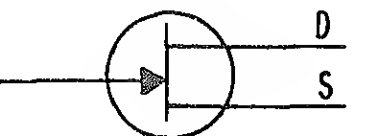
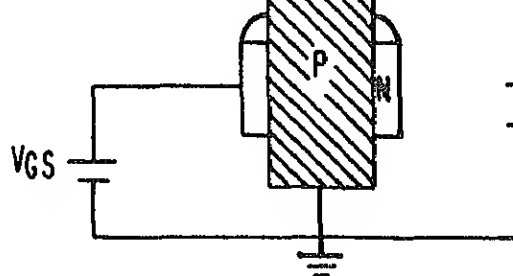
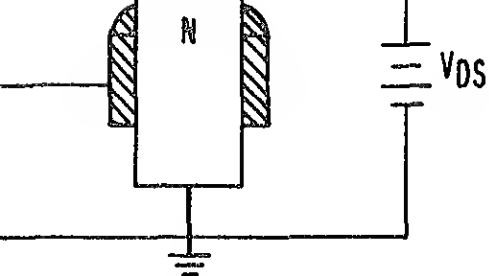


Figure 6 Signal Input to and Output from a

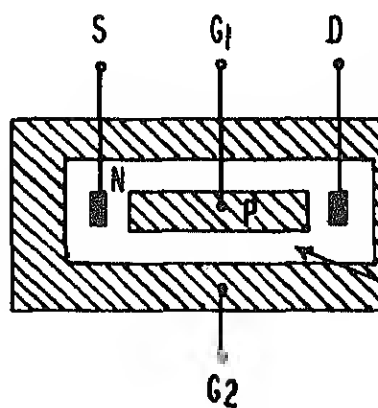
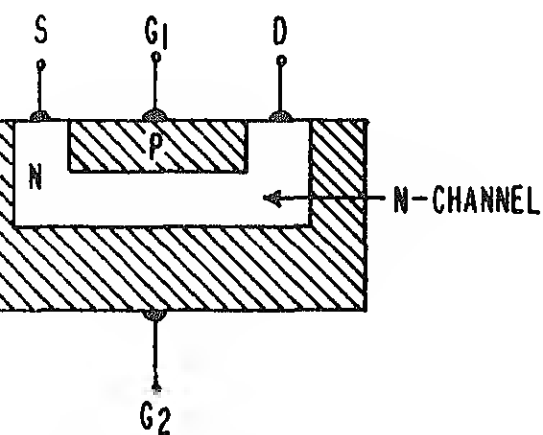
D. JFET Types

1. Field-effect transistors come in various structures. Just as there are PNP and NPN transistors, there are both N-channel and P-channel JFET's, as seen in figure 7. In a P-channel



(A) N-CHANNEL

(B) P-CHANNEL



(C) SIDE VIEW (TETRODE)

(D) TOP VIEW (TETRODE)

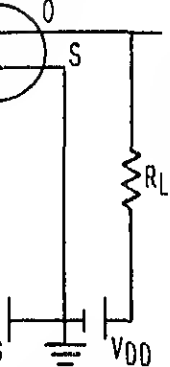


istor depends on the motion of both types of carriers. For this reason the conventional is called a bipolar type. The bipolar transistor has two junctions, one forward-biased and the other reverse-biased. It is the interaction between electrons and holes at the emitter junction which results in the diffusion current in the base that propels charges across the high electric field across the reverse-biased collector-base junction.

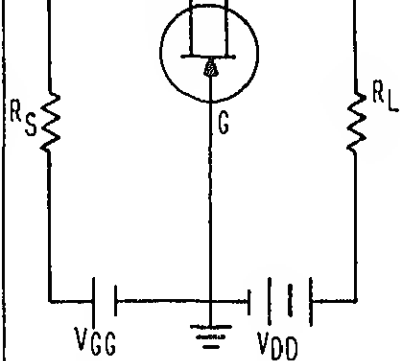
2. It is possible to include two gate elements in a single device from each other as shown in figures 7(c) and (d). Their symbols are shown in figures 7(e) and (f). They are available for mixing and other circuit applications such as AGC and d-c feedback, in which a d-c to a-c amplification is to be established. They are called dual-gate field-effect transistors. When the second input is not used, it is normally connected to the circuit so that its gate-channel junction is reverse-biased.

E. Basic Circuit Configurations

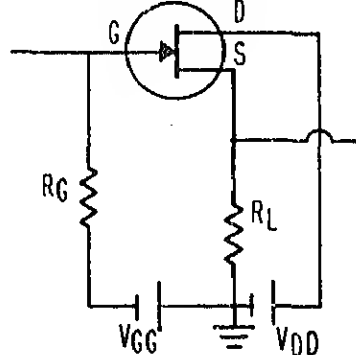
1. Like the vacuum tube and the bipolar transistor, the field-effect transistor can be connected in three basic arrangements (figure 8). Each has its individual characteristics. The common-source connection is most widely used. It has a good voltage gain, high input impedance, and a medium-to-high output impedance. Input signal is applied between the gate and the source and the output signal is developed between the drain and the source.
2. Input and output voltages are out-of-phase in the common-source example, a positive swing of the input to the gate-source junction FET increases the drain current through the channel. The resulting increase of drain current through the load resistance causes a decrease in the positive drain voltage. Conversely, a negative swing of the gate voltage decreases the drain current and increases the drain voltage.
3. The common-gate configuration's voltage gain is less than that of a common-source. Input impedance is low and output impedance is high; herefor...



High voltage gain
High input impedance
Low output impedance
Input and output 180° out of phase



Moderate voltage gain
Low input impedance
Moderate output impedance
Input and output in phase



No voltage gain
Very high input impedance
Low output impedance
Input and output in phase

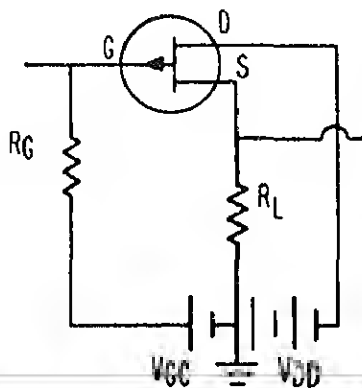
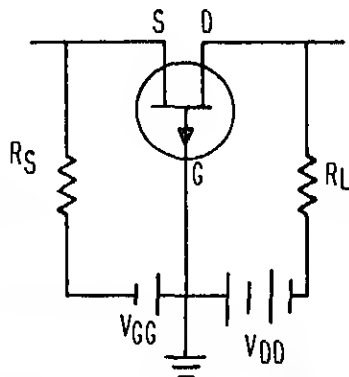
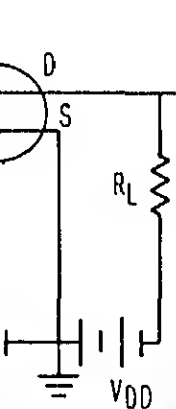


Figure 8 Basic JFET Circuits

4. Input and output voltages are in phase. Using the N-channel FET as an example, a swing of the gate voltage in the positive direction (same as a negative swing of the gate voltage) decreases the drain current and increases the drain voltage. Conversely, a swing of the source voltage increases the drain current and decreases the drain voltage.
5. The common-drain's (source follower) input impedance is very high, and the output impedance is low. The input impedance of the common drain can be compared to the input impedance of the common-gate. A current gain is possible but there is no voltage gain.
6. Input and output voltages are in-phase. For the N-channel JFET, a positive swing of the gate voltage increases the source-to-drain current. An increase in the source (output) voltage causes the drain current to decrease in the positive direction. Conversely, a negative swing of the gate voltage decreases the drain current and increases the source voltage.

F. Symbols

1. Standardization of alphabetical and graphical symbols in electronics continues to be a problem for manufacturers, industries, and engineering societies. The introduction of solid-state devices has resulted in some standardization, and certain procedures have become accepted. It should be stressed that, although it is now common to use the letter V for voltage, in electronic state symbology, the letter E continues to be used in relation to vacuum tubes.
2. When a current is specified, the first subscript indicates the element at which the current is measured. When a voltage is specified, the first subscript indicates the element at which the voltage is measured, and the second subscript indicates the reference point. When no second subscript is used, the voltage is measured with respect to the common (ground) as a reference point. The conventions of figure 9 are widely observed at the present time.

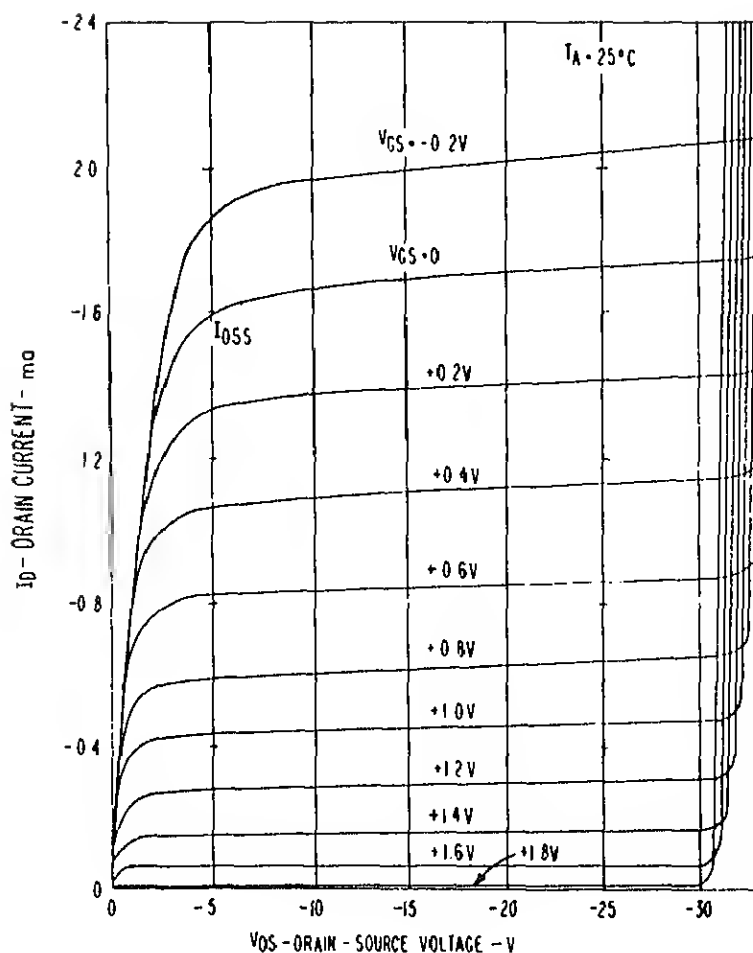
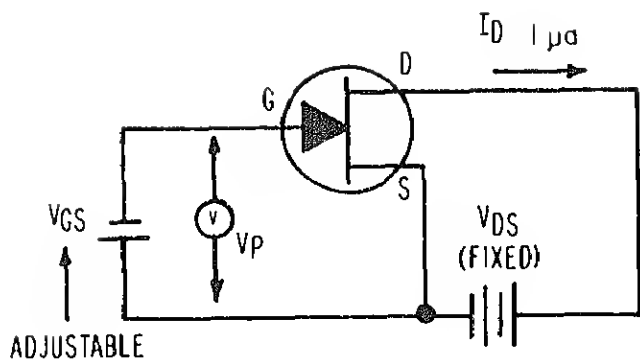
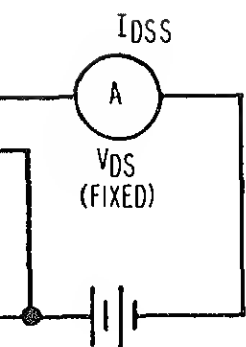
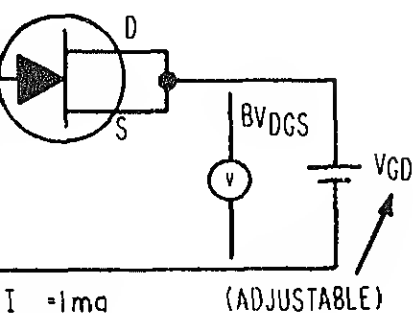


Figure 10 Typical JFET Output Characteristics for the 2N2608

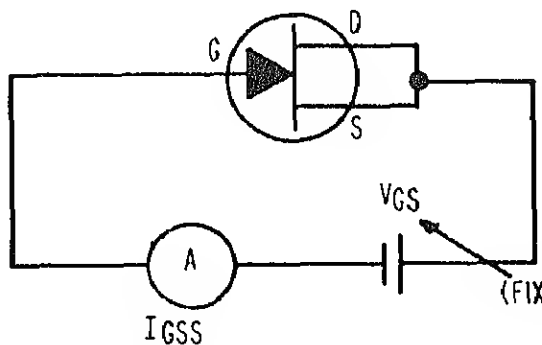


I_{DSS}

(B) V_P



(C) BV_{DS}



(D) I_{GSS}

Figure 11 Measuring Key Fet Parameters

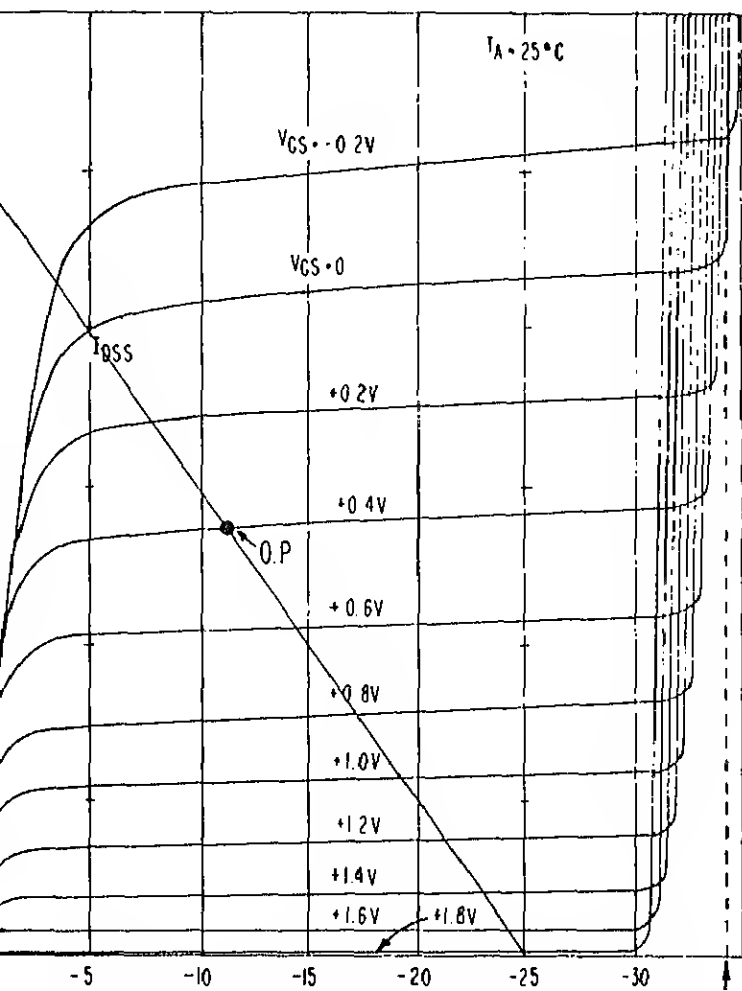
gate-bias voltage (V_{GS}) at which the drain current I_D be reduced to practically zero for a specified drain voltage (V_{DS}) is known as the gate-source pinch-off voltage (V_P). Some insignificant value of drain

	Parameter	Units	Min
SS	Gate-Source Cutoff Current at: $V_{GS} = 30V$ $V_{DS} = 0$	mA	
SS	Gate-Source Cutoff Current at: $V_{GS} = 5V$ $V_{DS} = 0$ $T_A = 150^{\circ}C$	μA	
GDS	Gate-Drain Breakdown Voltage at: $I_G = 1\mu A$ $V_{DS} = 0$	Volts	30
SS	Drain Current at Zero Gate Voltage: $V_{DS} = -5V$ $V_{GS} = 0$	mA	0.90
	Gate-Source Pinch-off Voltage at: $V_{DS} = -5V$ $I_D = 1\mu A$	volts	1
s	Small-Signal Common Source Forward Transconductance at: $V_{DS} = -5V$ $V_{GS} = 0$ $f = 1kHz$	μmho	1000
SS	Gate-Source Capacitance at: $V_{DS} = -5V$ $V_{GS} = 1V$ $f = 140 kHz$	pF	12
	Noise Figure at $V_{DS} = -5V$ $V_{GS} = 0$ $f_o = 1M$		

are certain maximum ratings which, if exceeded, result in the destruction of the transistor. A y of the key parameters and specifications for 3 as furnished by the manufacturer are shown in 1.

g a Load Line

line can be drawn (figure 12) on the FET's teristic curves.



2. At the operating point, the transconductance is about 1375 μmhos . Using the formula

$$A_v \approx g_{fs} R_L: A_v \approx (1375 \times 10^{-6})(12.5 \times 10^3)$$

The slight discrepancy in this case is because of error in reading the curves; however, the information is as accurate as most electronic data.

I. Noise Considerations

The noise content of a FET is low in comparison to a vacuum tube or a bipolar transistor. The three sources of noise in a field-effect transistor are: The gate-leakage current shot noise, thermal or resistance noise that results from the agitation of the charge carriers in the channel, and low-frequency noise (1/f noise).

J. Frequency Response

1. Low power junction FETs have a gate-to-drain capacitance (C_{gd}) ranging from 1 to 100 pF. This capacitance increases as the drain-to-source voltage approaches the pinch-off voltage. As a result, the capacitance (C_{gd}) the "Miller effect" occurs in junction FET's.
2. A regular (bipolar) transistor's low impedance input tends to shunt a large portion of the feedback signal from the transistor's high impedance internal feedback path to the emitter. The Miller effect in regular transistors is therefore, not as great as in FETs where the input signal at the gate, like the internal feedback signal, is usually also of high impedance.
3. The Miller effect in FETs can be reduced by reducing the drain to source voltage, reducing the drain resistance, the input impedance or with a feedback circuit that bypasses the semiconductor's internal feedback.
4. Theoretically, junction FETs should be able to operate at frequencies up to 1 GHz, although the maximum

can be made to operate well as common-source amplifiers at frequencies of several hundred megahertz.

Temperature Effects

Like JFETs, like regular transistors, are normally affected by changes in temperature (T_A). Measurements show that their pinch-off voltage (V_P) usually increases at about 0.2% per 8°C .

Although FET PN junctions are affected by temperatures, the current stability of silicon FETs approaches the current stability of bipolar silicon transistors. Provided the circuit's gate-to-source resistance (R_G) lies between 1 and 10 megohms.

Temperature effects of temperature change in JFETs result in a linear decrease in I_{DSS} with increasing temperature, causing the current to decrease about 0.6% per $^\circ\text{C}$. This drift can be reduced by operating the FET at a level of I_D .

JFETs with lower pinch-off voltages also show I_D drift. Measurements show that FET's having higher pinch-off voltages experience no temperature drift when operating at their normal I_{DSS} and g_{fs} .

Standardization--In a previous lesson, it was shown that transistors of the same type have exactly the same characteristics. The same problem exists with JFETs. Transistors of the same type have I_{DSS} and g_{fs} ratings that vary as much as 2 to 1.

Advantages and Disadvantages:

It would be apparent that the primary advantages of JFETs are:

- Very high input impedance.

- Low noise characteristics.

- Although their voltage gains are relatively low, once a saturation point occurs in a circuit, the bipolar

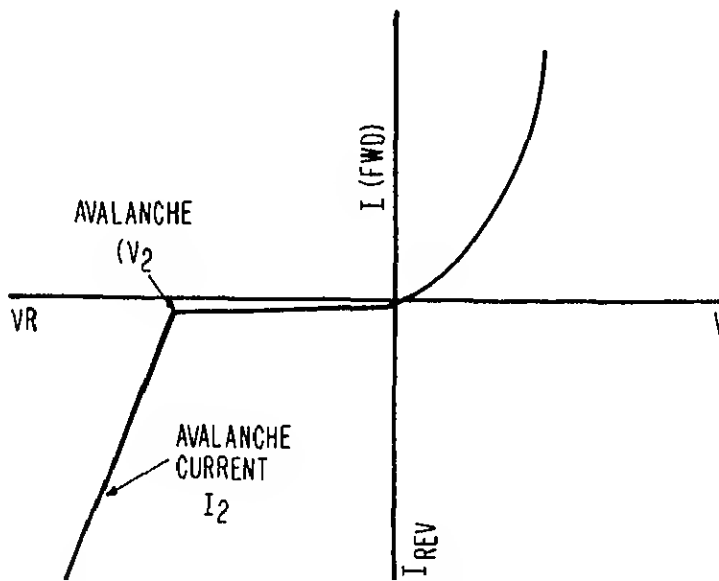
The reader must be aware that, although the characteristics are temperature sensitive, near as sensitive to T_A variations as the transistor.

II. AVALANCHE DEVICES

- A. Avalanche is defined as a cumulative process by which charged particles collide with and ionize the atoms through which they are traveling.
- B. As long as the current-handling capacity of the device is not exceeded during the avalanche process, some of the device characteristics can be utilized.

1. Zener Diode

A zener diode is a PN-junction diode that is more heavily doped than the average diode. It is designed to operate in the reverse bias breakdown region without damaging the junction. Since the zener diode operates in the reverse-bias direction, it operates on minority carriers.



breakdown (V_Z) occurs is determined by the type of semiconductor material used, the type of doping material used, and the actual doping level of the zener diode.

Once the diode goes into the avalanche region, the voltage across the diode will remain almost constant. The reverse-bias potential accelerates the minority carriers to such a velocity that they physically dislodge other carriers from the crystal lattice. The result is a very large current flowing in the zener diode. If the voltage applied to the junction decreases, the acceleration of the carriers will decrease, which results in less current through the diode. With less current flow, the zener impedance increases and the voltage across the diode remains constant.

The constant voltage characteristics of the zener diode (in the avalanche region) are particularly useful in voltage regulator circuits.

Figure 14 is a basic voltage regulator circuit employing a zener diode as the regulating component.

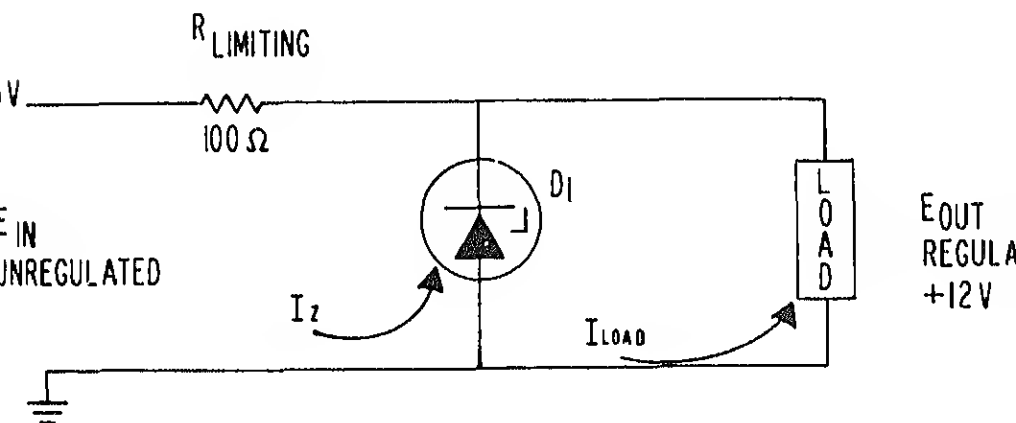


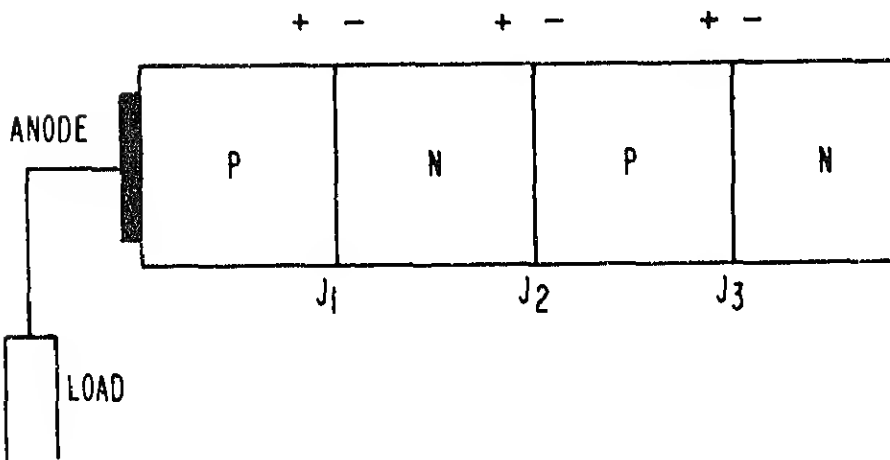
Figure 14

rent flow through R_{limiting} decreases output returns to +12 volts.

- b. If the unregulated voltage increases, supplied to the zener diode will increase. The increased voltage (V_Z) will cause an increase in I_Z . When I_Z increases, the voltage drop across R_{limiting} will increase, thus returning the regulated output to +12 volts.

2. Four-layer diodes (PNPN)

- a. A PNPN diode is a 4-layer, 3-junction device that operates in the avalanche mode.
- b. As shown in figure 15, the layers are doped P- and N-type semiconductor materials. The P-type regions are connected to ohmic contacts to the P-type and N-type regions. The ohmic contact to the P-type region is called the anode, and the contact to the N-type region is called the cathode. Notice that the P- and N-regions are floating.



said to be "OFF" or blocking, which represents a high resistance between anode and cathode.

With J2 reverse-biased, only minority carriers flow through the internal P- and N-areas. The negative voltage on the N-type cathode injects electrons into the internal P-type area where they flow as minority carriers, and the positive voltage on the P-type anode injects carriers into the internal N-type area where they also flow as minority carriers.

As can be seen in figure 15, as the applied voltage (V_F) is increased, more injected holes from the P-type anode will diffuse through the internal N-type material and be controlled by the internal P-type material. The internal P-type material becomes more positively charged (contains more holes), thus increasing the forward-bias on J3.

At the same time J3 is increasing its forward-bias, the N-type cathode is injecting more carriers into the internal P-type material which diffuse into the internal N-type region which becomes more negatively charged (more electrons) increasing forward-bias at J1.

As J1 and J3 increases their forward bias, their junction resistance decreases and more of the applied voltage (V_F) is felt at the reverse-bias junction J2, increasing the depletion region at J2.

As the depletion region at J2 increases, the effective N and P areas are reduced.

Figure 16 depicts the condition now existing; i.e. the increased depletion region at J2 and the reduced effective areas of the internal N and P-type materials. As the external voltage (V_F) continues to increase, the carriers crossing the depletion region gain velocity as they are swept across the junction. When the velocity the carriers gain while crossing the junction is great enough, free carriers are reduced in the internal N- and P-type

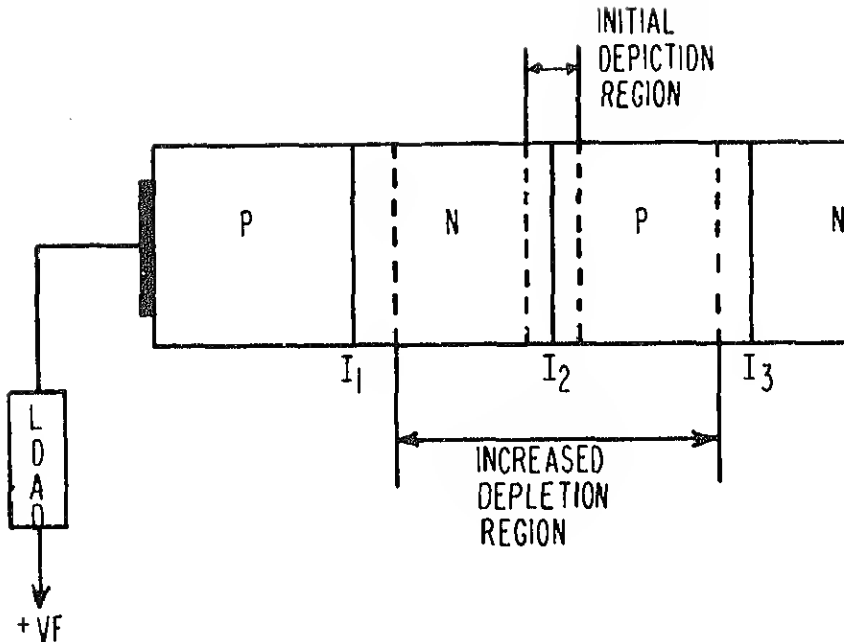
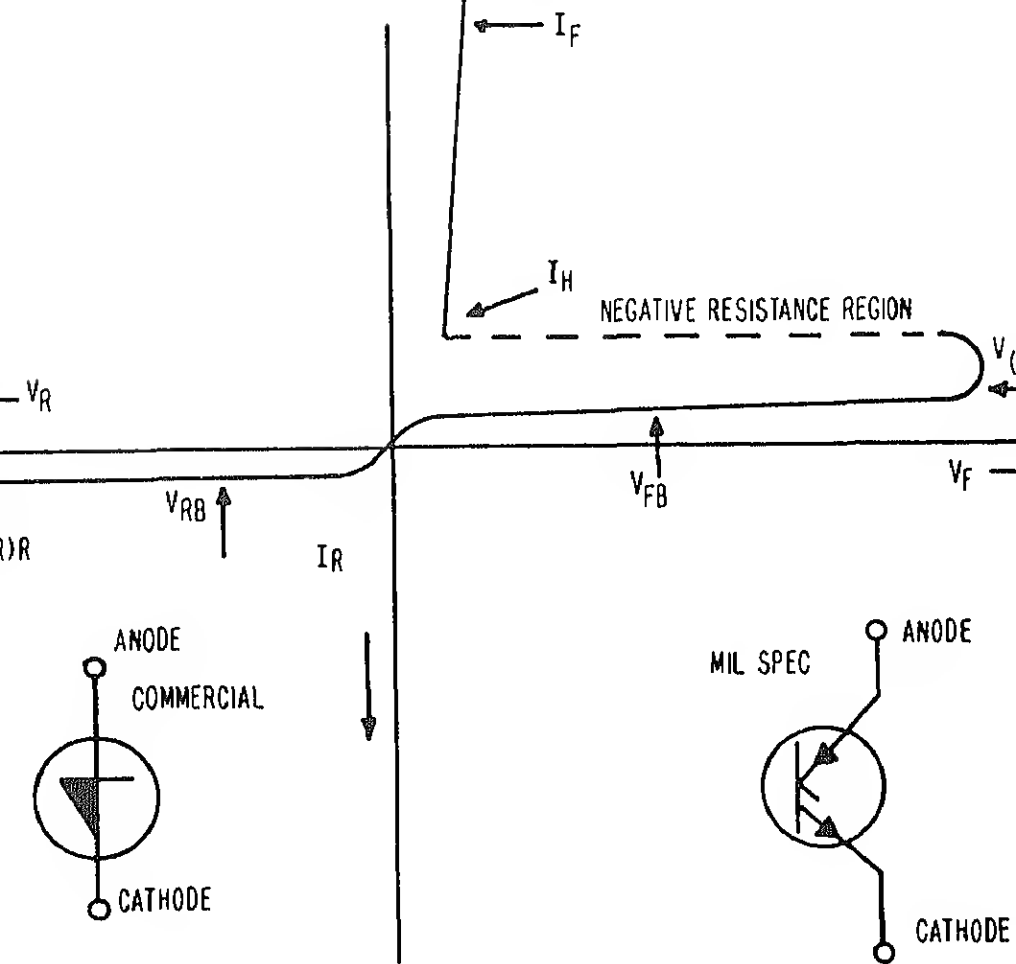


Figure 16

- j. This process is accumulative and anode starts increasing rapidly because of the carriers generated. Avalanche soon occurs. The current must be limited by external resistance or else the device will destroy itself. The device is said to be switched "ON" and has a low resistance between anode and cathode.
- k. The PNP device thus acts as a switch. In the off state, it has a high resistance, very low current flow. When the device is turned on, it has a low resistance, heavy current flow. When the device is turned on, a specific amount of current (I_F) must be maintained to keep it on. The current is specified as holding current, which is the current rating that must be considered. The latching current is a value of anode current, slightly higher than the holding current, which is the minimum current required to sustain conduction immediately after the device is switched ON. In other words



PNPN CHARACTERISTIC GRAPH

Figure 17

The applied voltage V_F , anode positive to cathode, that results in a small current flow is called the forward blocking voltage, V_{FB} . As the forward voltage is increased, a sudden increase in current is apparent as the device switches "ON." The minimum voltage necessary to turn the device on is

i.e., as reverse-bias, V_R , is increased a will occur at the reverse breakdown point $V_{(BR)R}$. The PNPN switch can be destroyed reverse-bias avalanche region and should operated with reverse-bias between anode cathode.

- o. PNPN switches are used for trigger device low-cost sweep generators and timers.
- p. Figure 18 is another sweep-generator circuit using a PNPN switch.

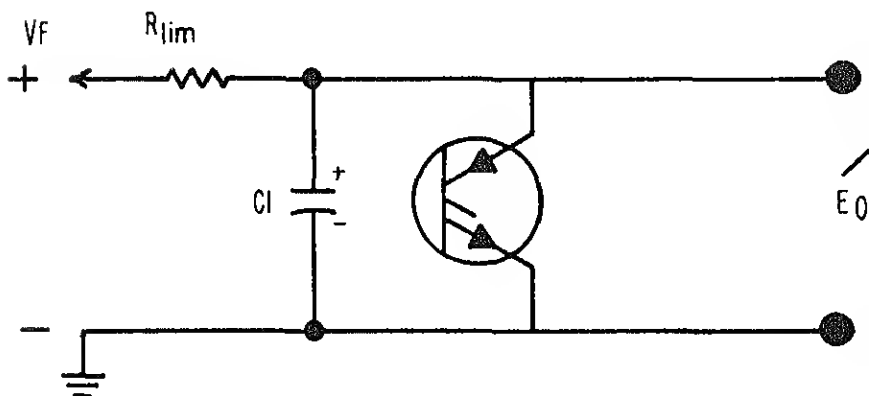


Figure 18

When V_F is applied to the anode of the PNPN switch, the capacitor starts charging toward V_F . When the voltage across the capacitor reaches $V_{(BR)R}$, the diode turns ON and discharges the capacitor. A sawtooth waveform is thus produced across the load resistor. R_{lim} limits the current to a safe value, and $C1$ determines the rate of firing.

3. Silicon Controlled Rectifiers (SCR)

- a. Basically, the SCR is a PNPN structure with an ohmic contact made to the internal P-type

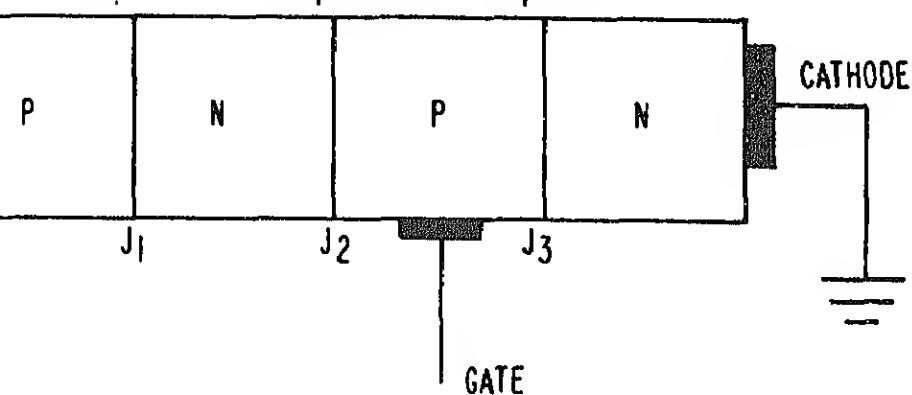


Figure 19

The additional lead is called the gate and aids in the "turn-on process."

The SCR is normally operated with $V_F \ll V_{(BR)F}$, where $V_{(BR)F}$ represents the forward breakover voltage, as was the case with the basic PNPN device. With the gate open, the SCR will be "OFF" in the blocked condition. When a positive voltage is applied to the gate, current will flow into the gate (I_{GT}).

The current flow (electrons) in the gate is injected from the N-type cathode; however, many injected carriers will diffuse through the internal P-type material to the internal N-type material. The internal N-type material now takes on a negative charge (excess electrons) increasing the forward bias on J1. The increased forward-bias on J1 increases injected holes through J2 from the anode.

process just described and also including commercial and Mil-Spec symbols for the

- g. Notice that as I_{gate} is increased, turn (breakover) occurs at lower values of quite an advantage over the basic PNPN there was no control over the breakover.
- h. Also apparent in figure 20 is the fact acts as a bistable switch; i.e., "ON" V_F is a positive voltage and V_{gate} is positive.
- i. The SCR is the solid state equivalent of a thyatron tube which is switched by a voltage pulse on its control grid which is a tube. The SCR on the other hand receives a pulse on its gate which aids in the "turn on" process in much the same manner as a thyatron. Like the thyatron's grid, the SCR's gate controls the device once the device turns on. The device is turned off in the same manner that the thyatron was.

(1) Reducing the anode-cathode voltage to zero.

(2) Driving $I_F < I_H$.

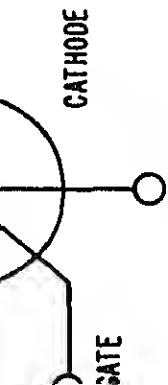
(3) Forcing commutation.

- j. The main advantage of the SCR is its ability to control heavy load currents with light (gate) currents. Currently SCR's have many applications among them, being; motor speed controls, heating controls, and ignition systems.
- k. As stated earlier, the SCR may be turned off by several methods:

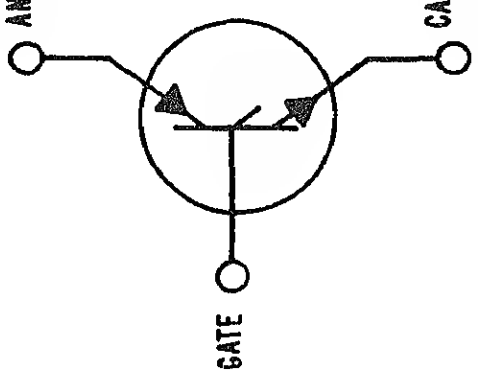
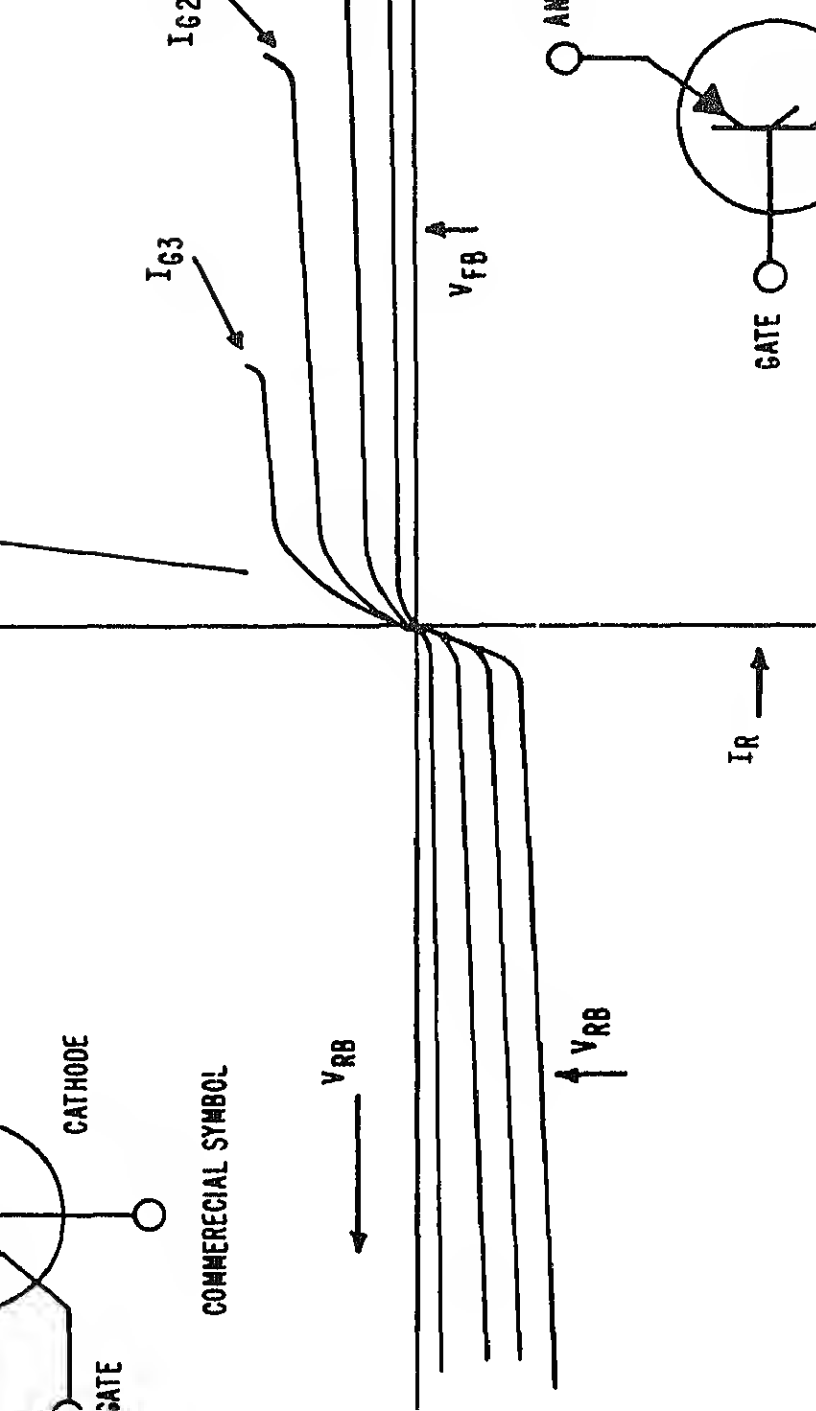
(1) Reducing anode current to zero.

(2) Driving I_F to $< I_H$.

(3) Commutation.



COMMERCIAL SYMBOL



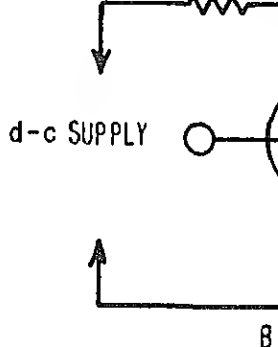
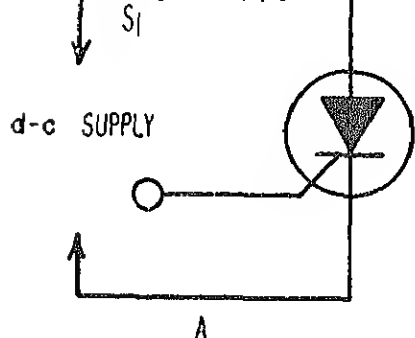


Figure 21

Figures 21a and 21b will definitely "fit" for conditions (1) and (2) above; however, it will be difficult to operate the switch at a very high frequency or with any appreciable current. The most often used "turn off" technique is the most often used "turn off" technique employed. This method switches current from one energy source to force current through the load in the reverse direction. There are six distinct classes of commutation.

- (1) Class A - Self-commutated by resonant load.
- (2) Class B - Self-commutated by an LC circuit.
- (3) Class C - C or LC switched by another thyristor carrying SCR.
- (4) Class D - C or LC switched by an auxiliary thyristor.
- (5) Class E - An external pulse source for commutation.
- (6) Class F - A-c line commutation.

1. As class F, a-c line commutation is the most common turn-off technique used; it will be the most common analyzed. Figure 22 will be used in the

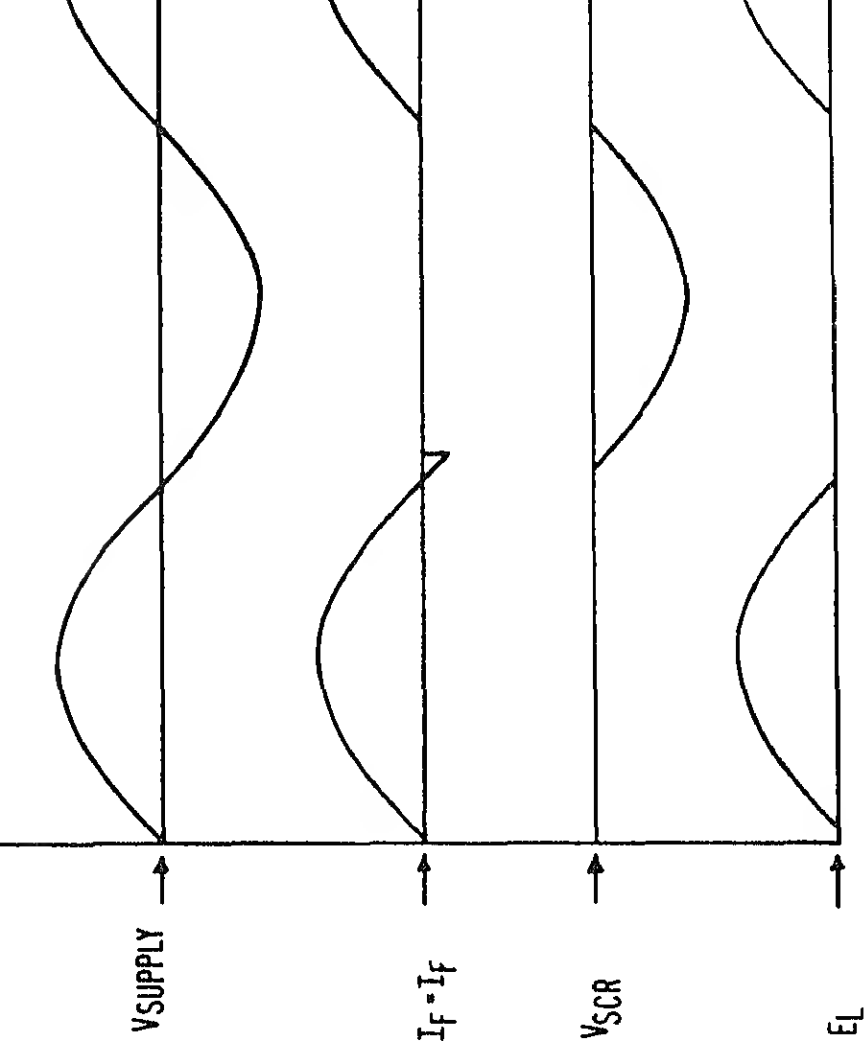
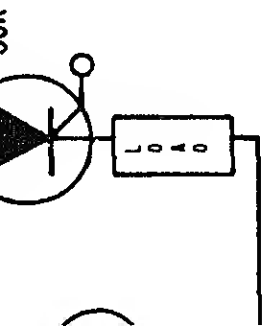
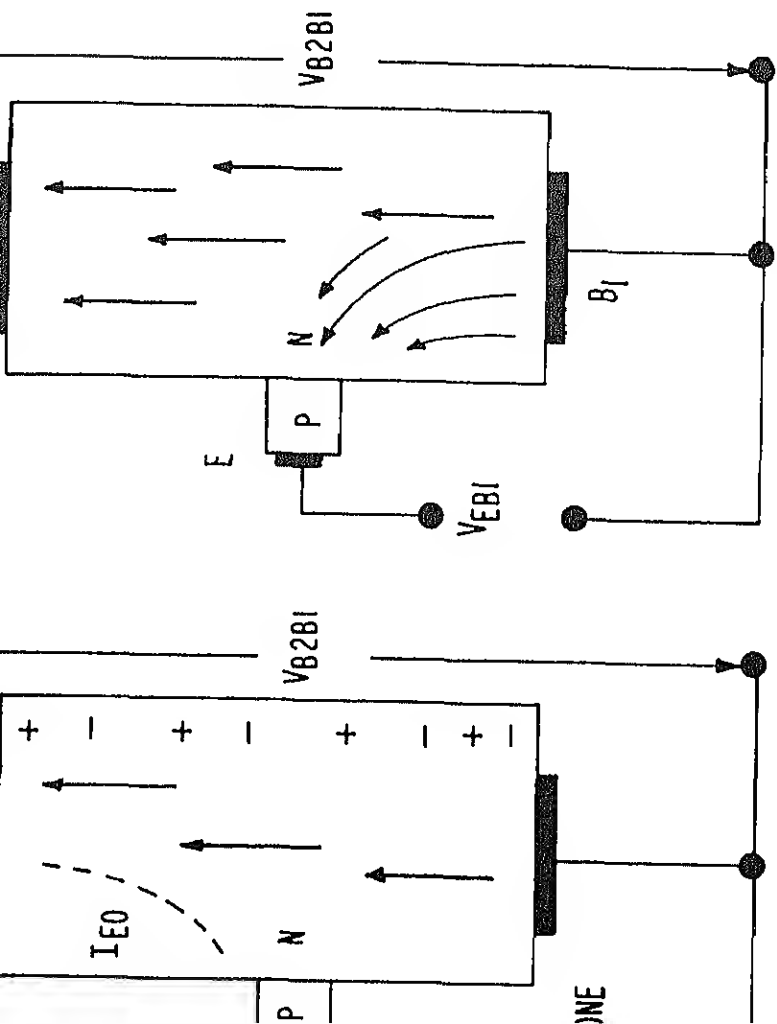
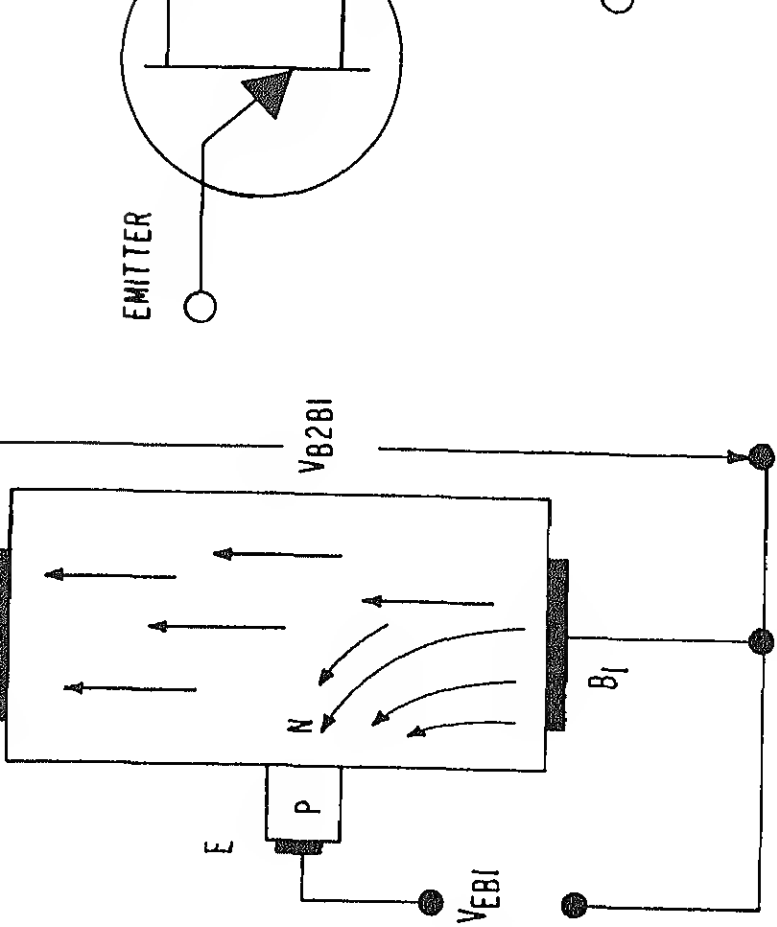


Figure 22

- A. The unijunction transistor (UJT) is basically with two contacts and a PN junction.
- B. Figure 23 shows the construction of an UJT and symbol.
 1. The two ohmic contacts made to the base (s are called B_1 and B_2 (N-type material). B_1 is the potential or common side and B_2 is the high or voltage supply side. B_2 will be biased respect to B_1 (V_{B2B1}).
 2. The PN junction formed is the emitter which is positive in respect to B_1 .
 - a. R_{BB} is the interbase resistance between B_1 and B_2 with typical values ranging from 4 kΩ.
 - b. Figure 23A depicts the condition existing at the emitter base junction with a voltage V_{EB1} applied. V_{B2B1} leads (V_{B2B1}) and the emitter voltage is equal to zero.
 - c. With V_{B2B1} applied, R_{BB} develops voltage drop throughout the N-type silicon bar. The voltage drop is opposite the PN junction, between B_2 and B_1 is some positive value.
 - d. Under these conditions, the PN junction is reverse biased and only a small amount of leakage current (I_{EO}) will flow in the emitter lead. The total current flow in the device will be essentially zero.
 - e. As shown in figure 23B, as the emitter voltage V_{EB1} is increased, positive in respect to B_1 , the PN junction will become forward biased.
 - (1) The emitter injects holes into the base where they are swept toward B_1 .
 - (2) Electrons from B_1 combine with the holes increasing I_E (emitter current).



(A)



(B)

(C)

Unijunction Transistor
Figure 23

4. Thus, the unijunction transistor has many characteristics of a gas thyatron. Until the collector voltage (V_{EB1}) reaches a certain value (V_p), it is reverse-biased and essentially cut off. When the critical value is exceeded, the emitter becomes forward-biased and emitter current increases considerably.
5. A simplified equivalent circuit for the unijunction transistor may be developed as shown in figure 24.

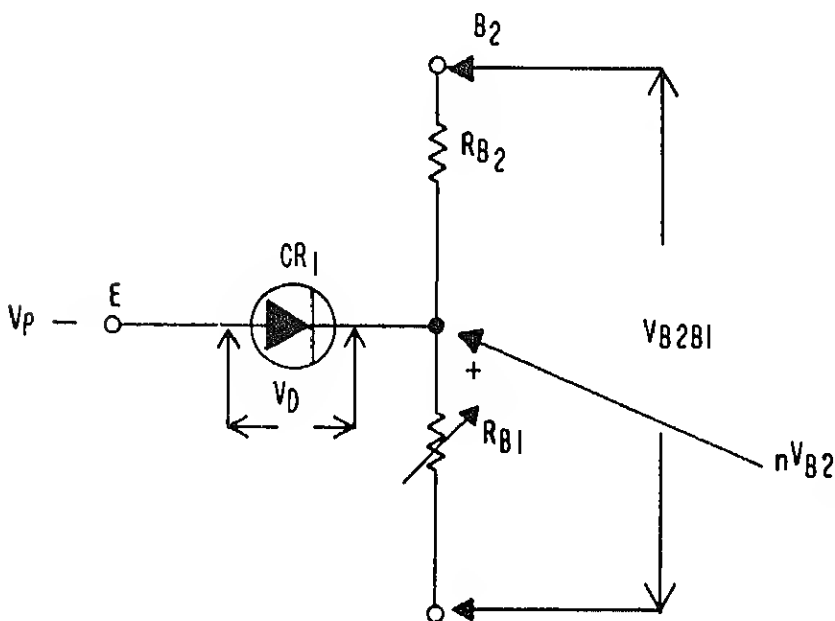
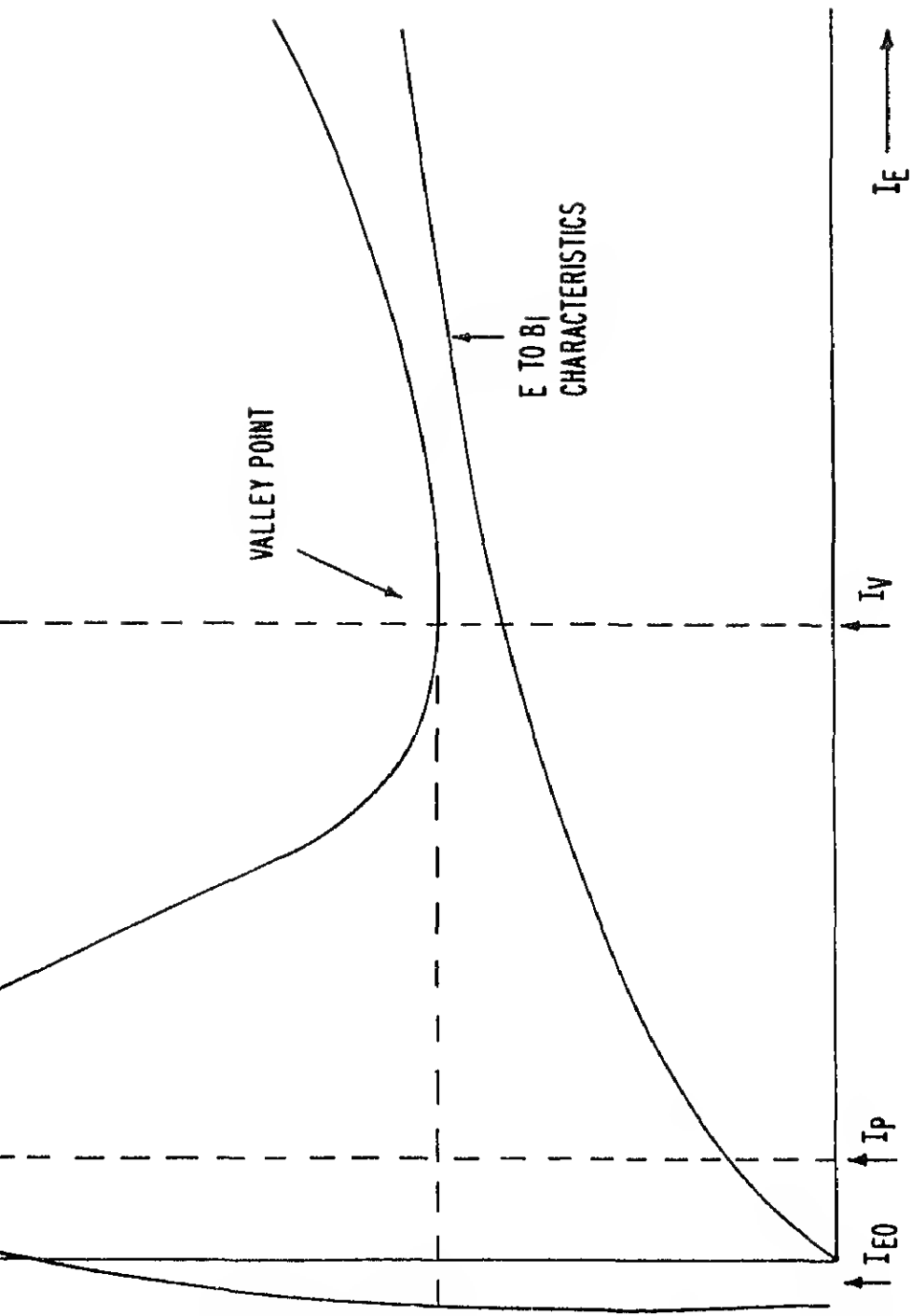


Figure 24

Diode CR_1 represents the emitter-bar PN junction. R_{B1} representing the resistance of base 1 and R_{B2} representing the resistance of base 2. R_{B1} is a variable since it does vary as a function of the emitter current.



is called the intrinsic standoff ratio and the percentage of the voltage V_{B2B1} developed across R_{B1} . The manufacturer of the UJT supplies this ratio in his specification sheet (typical values range from 0.51 to 0.82).

7. Also shown in figure 24 is a voltage drop across the diode CR_1 V_D . This voltage will be present in a static condition because of I_{EO} .
8. In order to turn the UJT on, the emitter voltage must be positive with respect to nV_{B2B1} . Thus, $V_E > nV_{B2B1} + V_D$. For example:

Given: $V_{B2B1} = 10$ volts
 $2N2646 \quad \eta = .51$
 Characteristics $V_D = .5$ volts

Find: The minimum voltage required to turn on the UJT (V_p).

Solution: $V_p = nV_{B2B1} + V_D$
 $V_p = (.51)(10V) + .5$
 $V_p = 5.6$ volts

- C. A typical characteristic curve of a unijunction transistor is shown in figure 25. This curve has three distinct regions. Region 1 is the cutoff region, where the device is reverse-biased. As the voltage applied between the emitter and B_1 rises, the current (I_E) rises slightly, but the total current seldom exceeds $10 \mu A$ (I_{EO}). Region 2, when the applied voltage reaches the point marked on the curve, the UJT "fires" with a large increase in current and a decrease in the voltage drop between the emitter and B_1 . This is the negative resistance region, a feature which gives the UJT its unique properties. We shall see presently. Eventually there is a point called the minimum, or valley point, beyond which the device behaves as a positive resistor. That is, the current increases slowly with voltage. This region is called the saturation region. The UJT switches from the cutoff to the saturation region quite rapidly, bypassing the highly unstable negative resistance region.

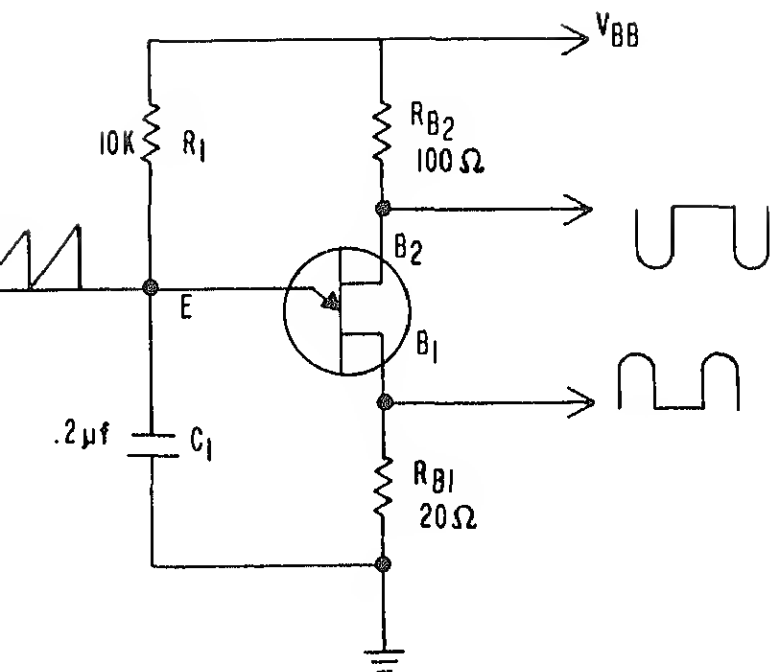


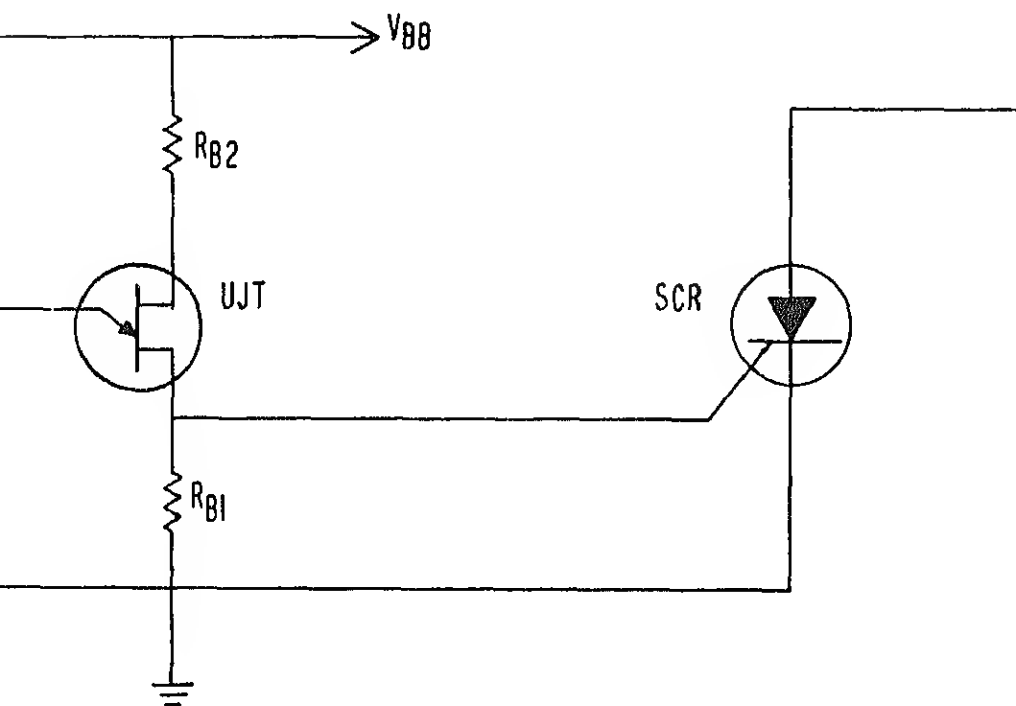
Figure 26

When the power supply (V_{BB}) is applied through R_1 , it will slowly charge the capacitor C_1 until enough voltage develops across C_1 to forward-bias the emitter junction (V_p). At this point, the unijunction transistor "fires." C_1 now discharges rapidly through R_{B1} and the low resistance of the emitter - B_1 junction. With C_1 discharged, the transistor returns to its nonconducting state, and the cycle repeats itself.

The waveforms developed in this circuit are also shown in Figure 26. The voltage across C_1 is a sawtooth wave, possessing a slow rise and a rapid descent. At the time of firing, the current through the entire emitter bar rises, developing a positive pulse at the top of R_{B2} and a negative pulse at the bottom of R_{B1} . Despite the extreme simplicity of this circuit, requiring

Figure 27 is another typical UJT trigger as used to control an SCR.

1. R_{B1} develops the positive trigger pulses necessary to trigger the SCR.



UJT CONTROL OF AN SCR

Figure 27

Circuits, NAVSHIPS 0967-000-0120

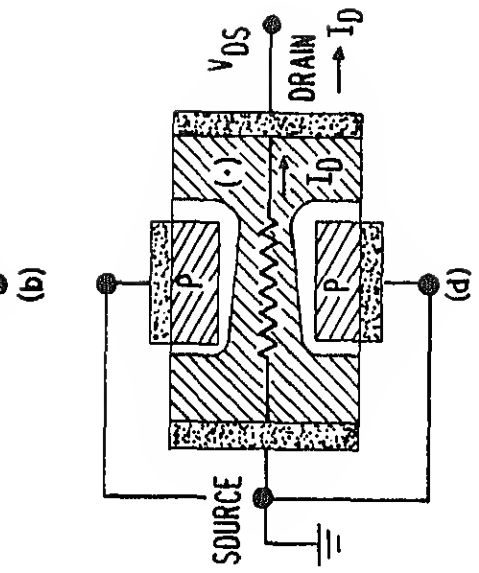
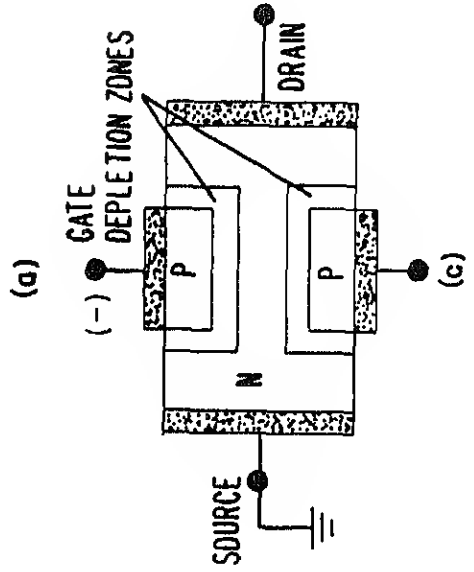
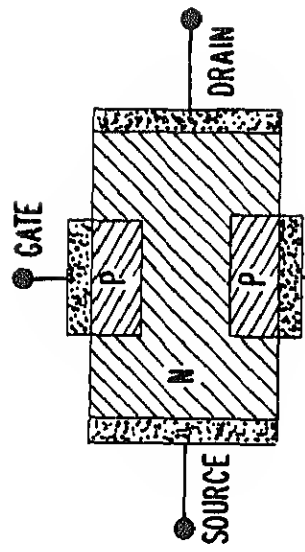
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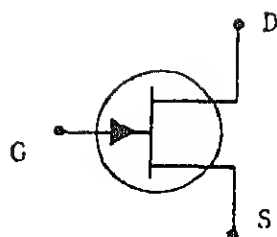
Malvino, Ph.D., Electronic Principles, McGraw Hill
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PLINE

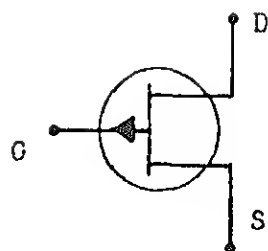
lon Field-Effect Transistors



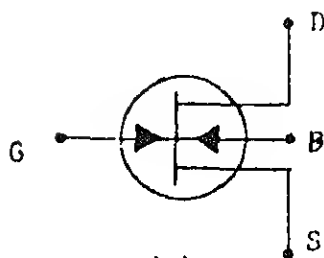
DEVELOPMENT OF JUNCTION FIELD-EFFECT TRANSISTOR



(a)
N-Channel

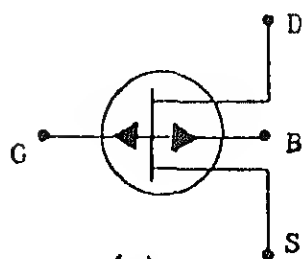


(b)
P-Channel



(c)
N-Channel

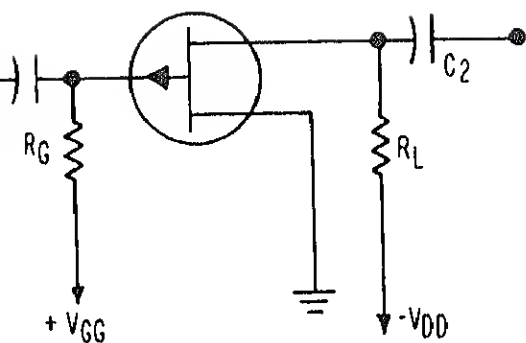
P-Substrate



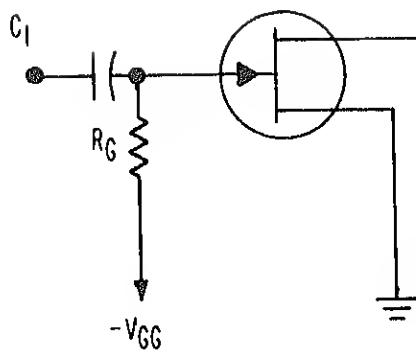
(d)
P-Channel

N-Substrate

ology

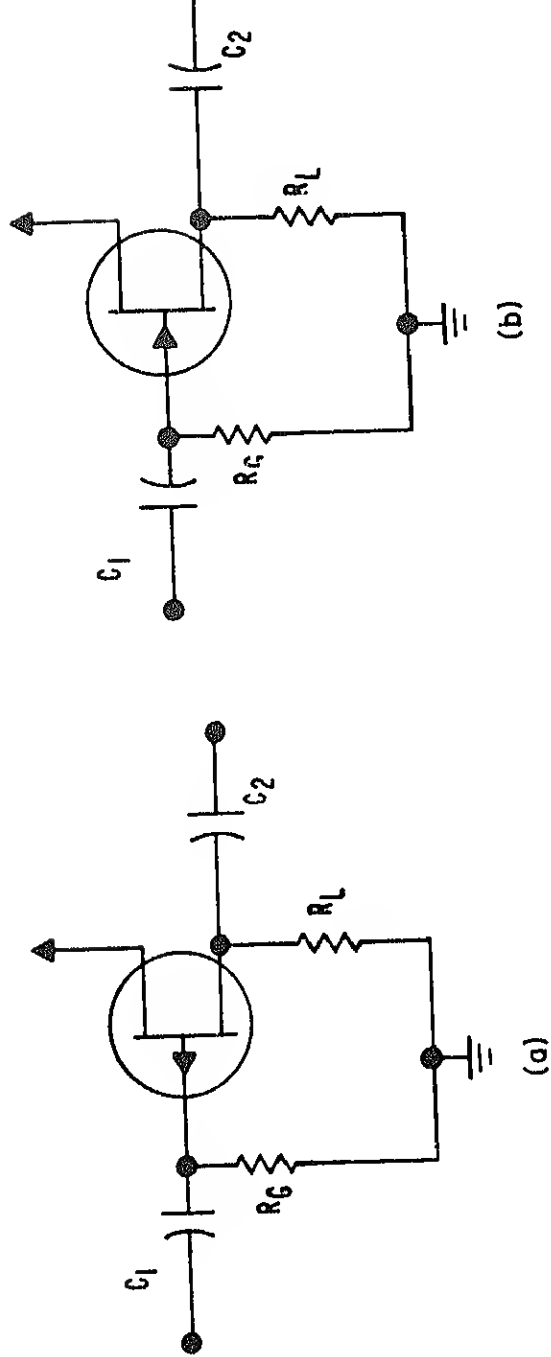


(a)
P-CHANNEL

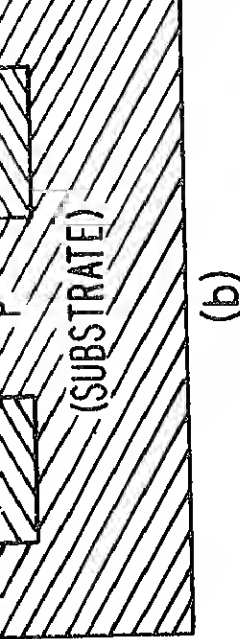
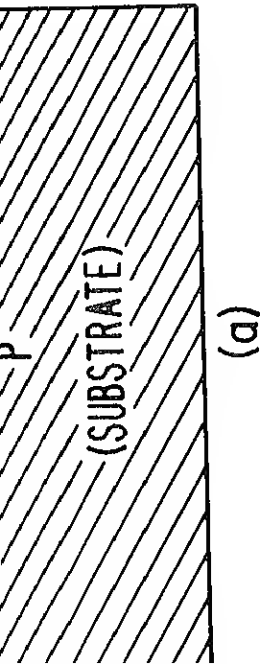


(b)
N-CHANNEL

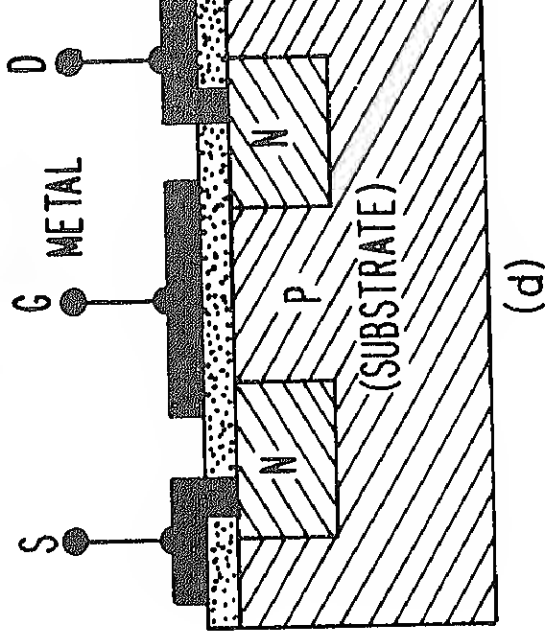
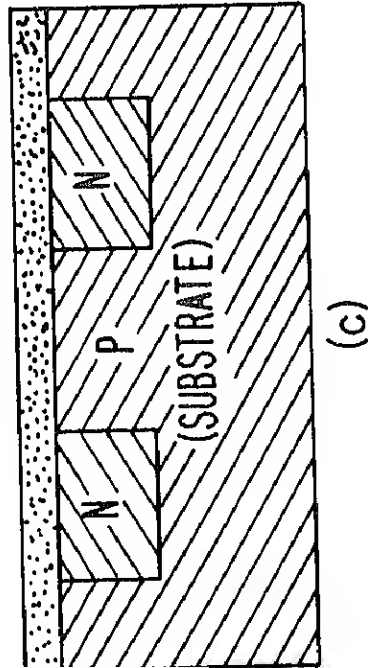
JFET COMMON SOURCE AMPLIFIER



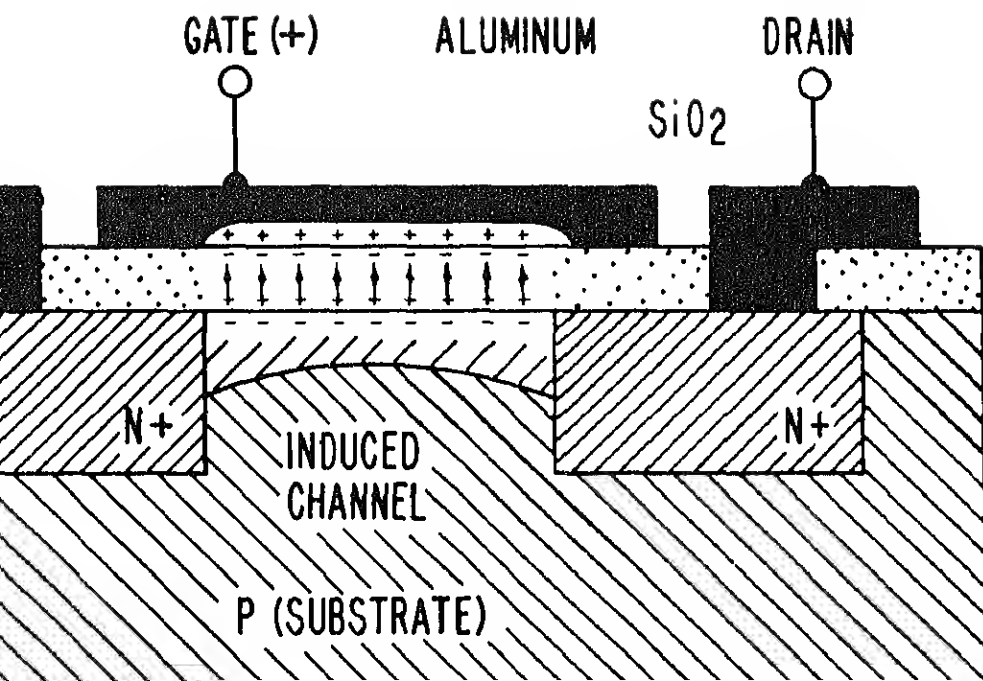
JFET CD AMPLIFIERS
Figure 6

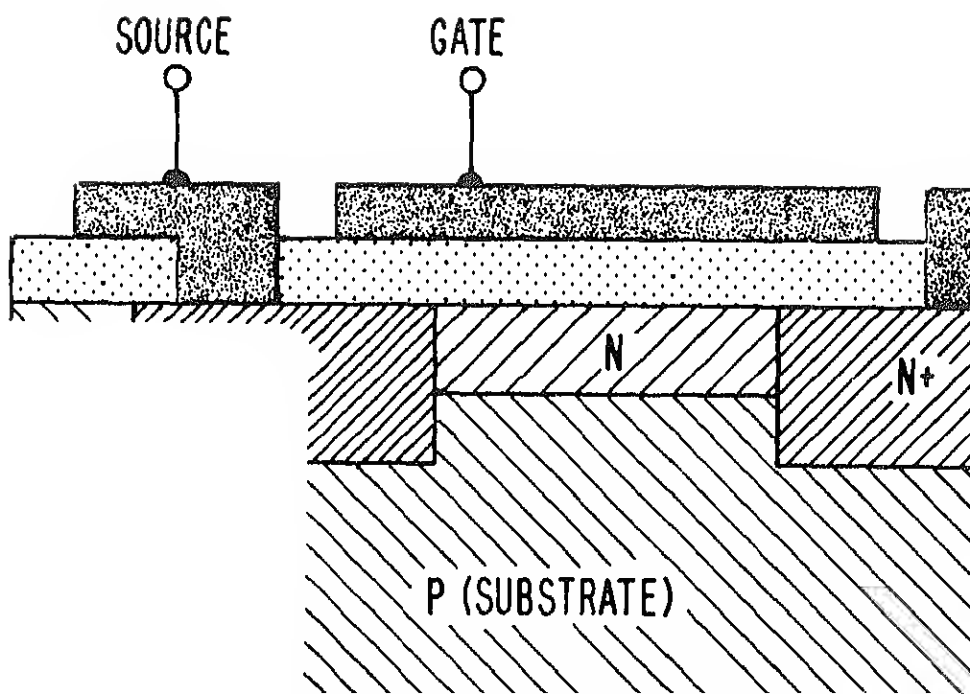


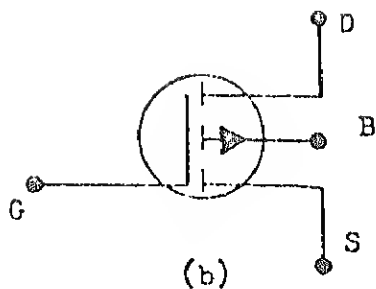
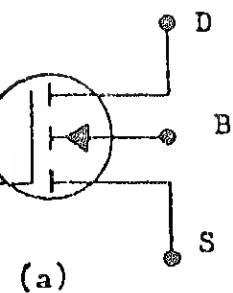
OXIDE



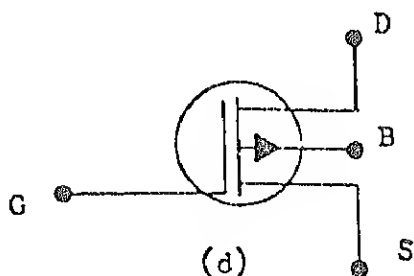
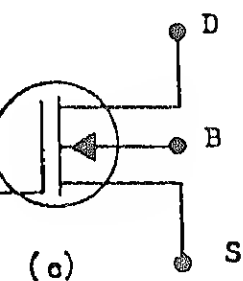
ENHANCEMENT MOSFET CONSTRUCTION







ENHANCEMENT



DEPLETION

MOSFET Symbols

Figure 11

VI. Avalanche devices

A. Zener Diodes

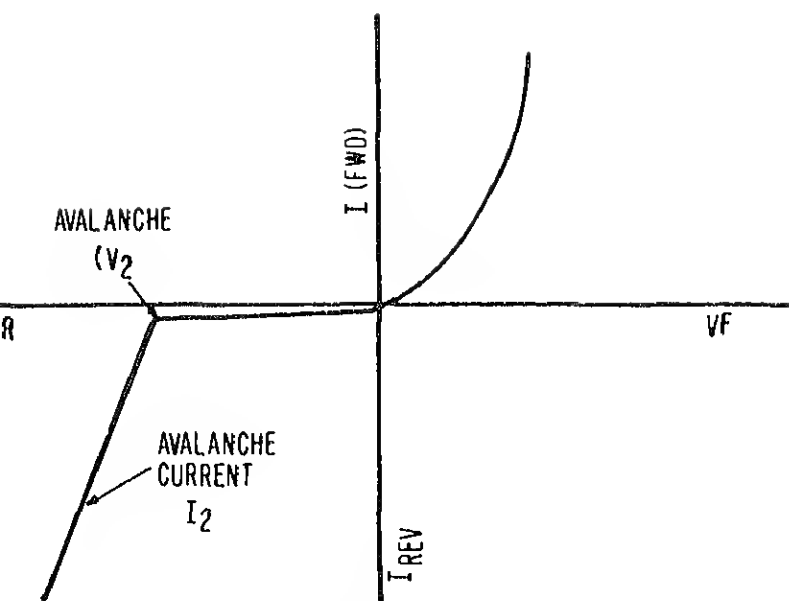


Figure 12

Diodes

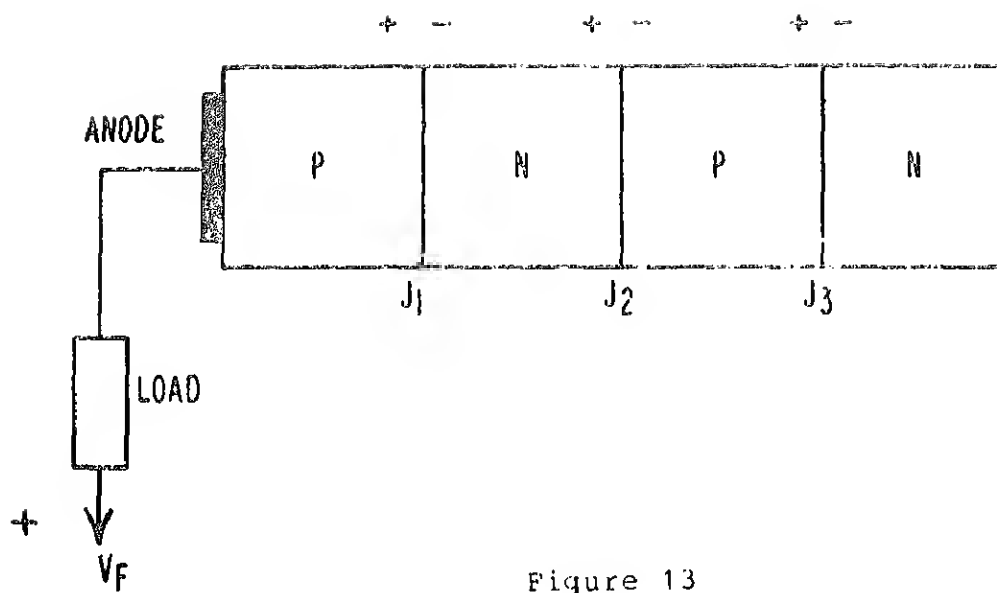
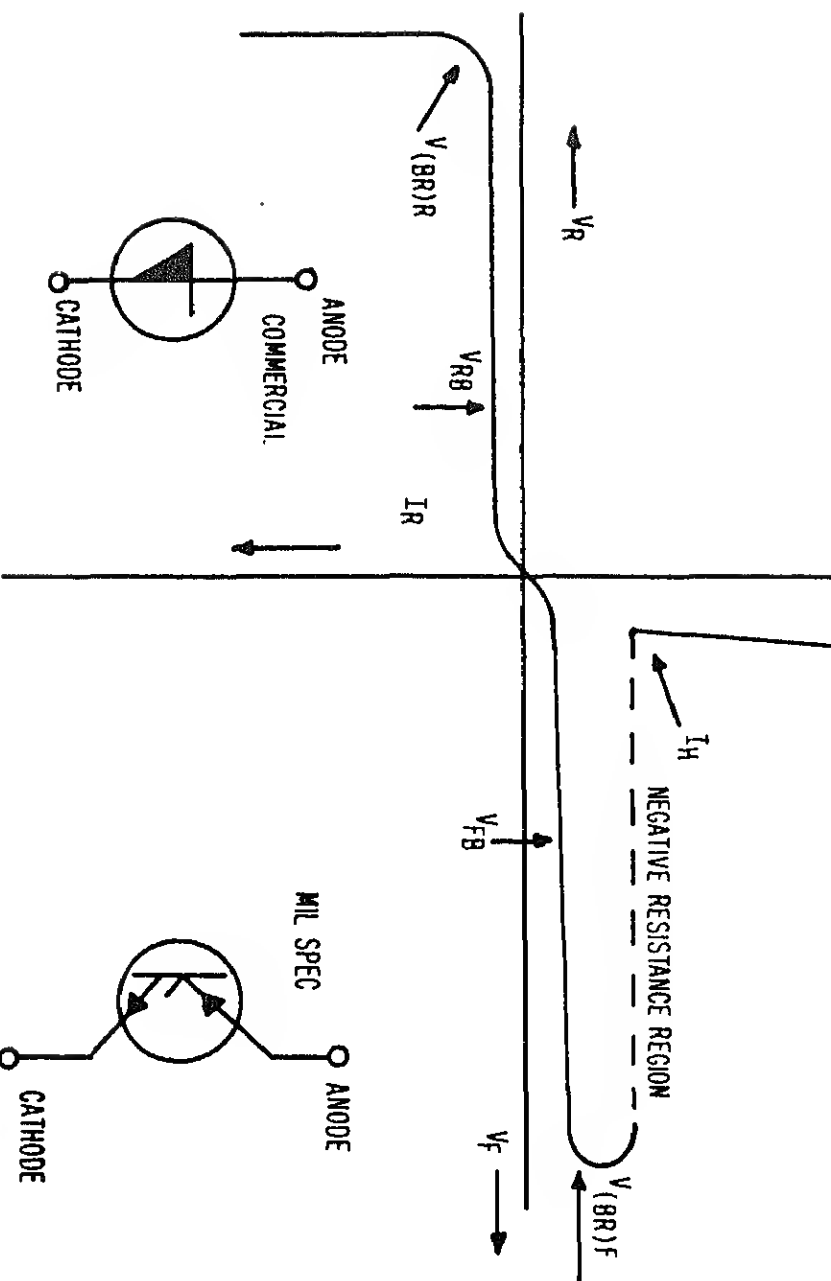


Figure 13



PNPN CHARACTERISTIC GRAPH

Figure 14

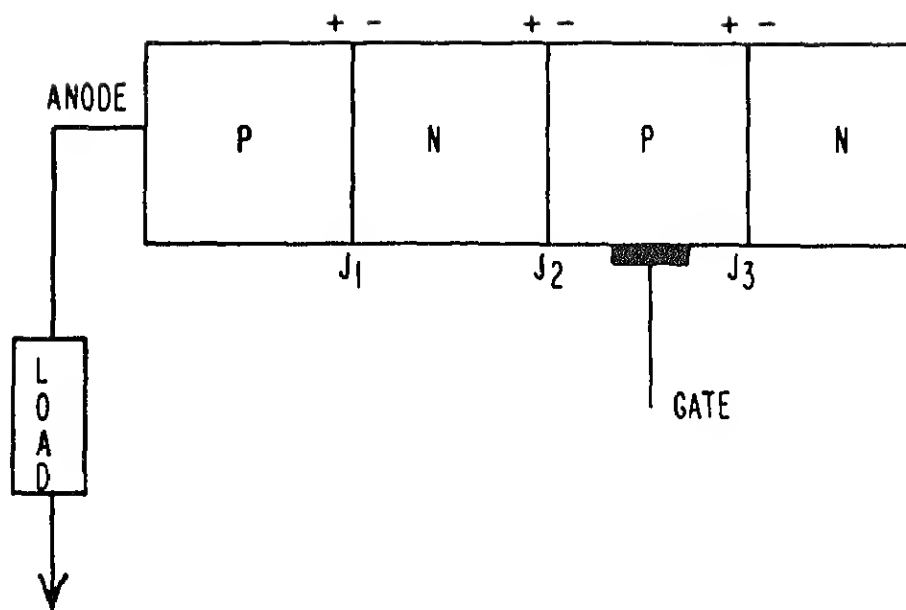
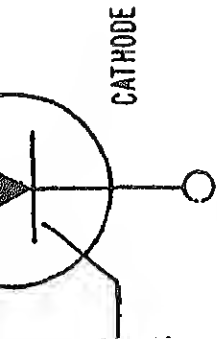


Figure 15--Silicon-Controlled Rectifier



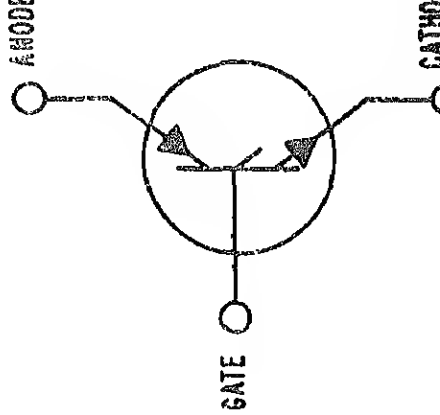
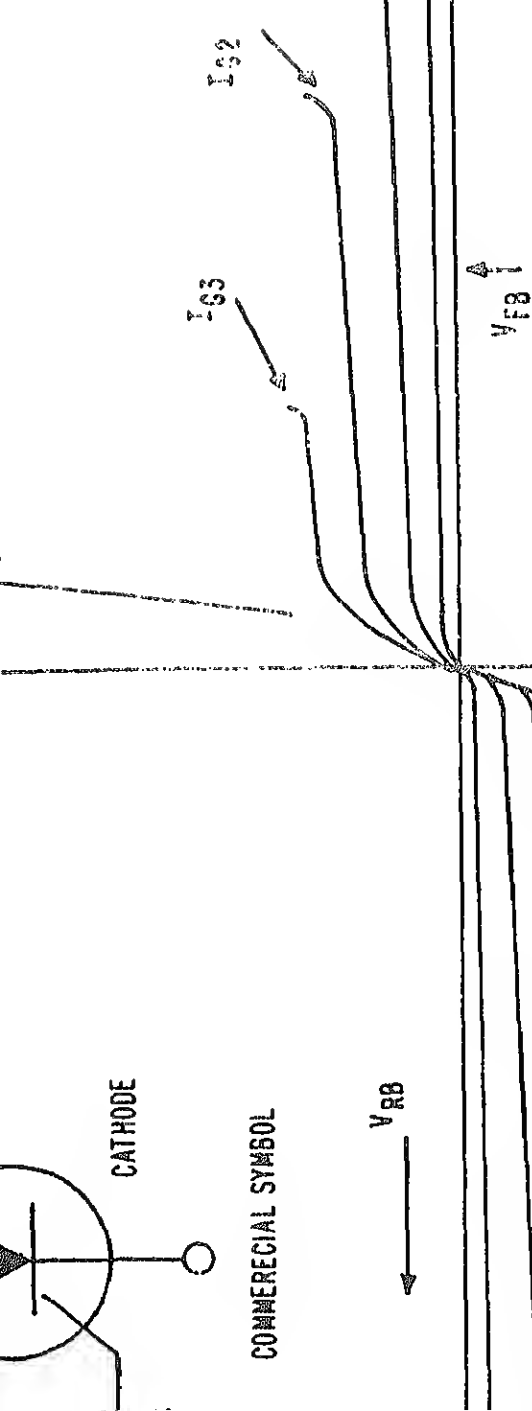
CATHODE

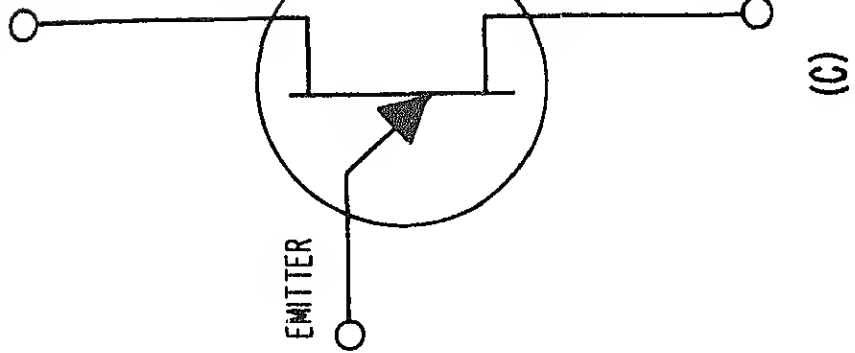
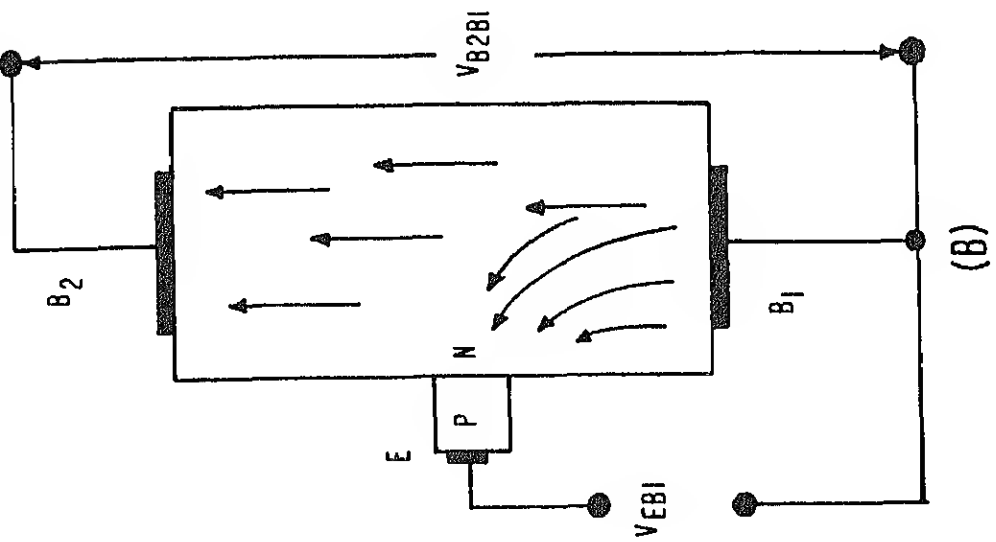
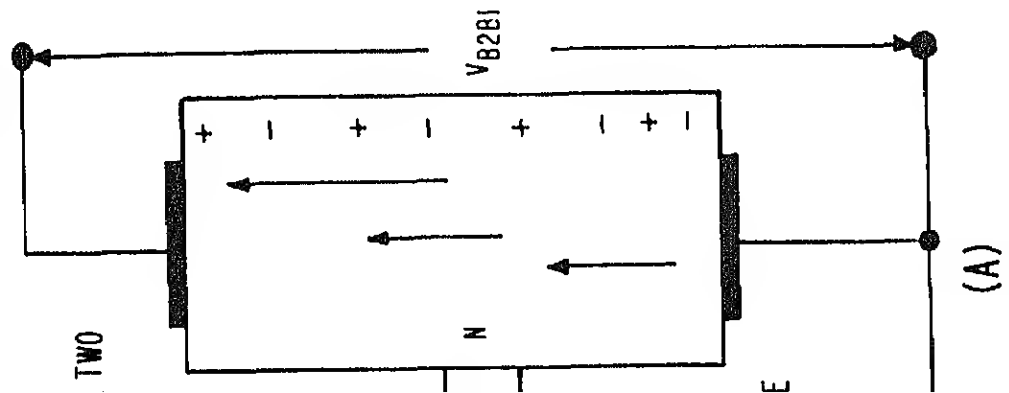
COMMERCIAL SYMBOL

V_{RB} →

↑ V_{RB}

I_R →

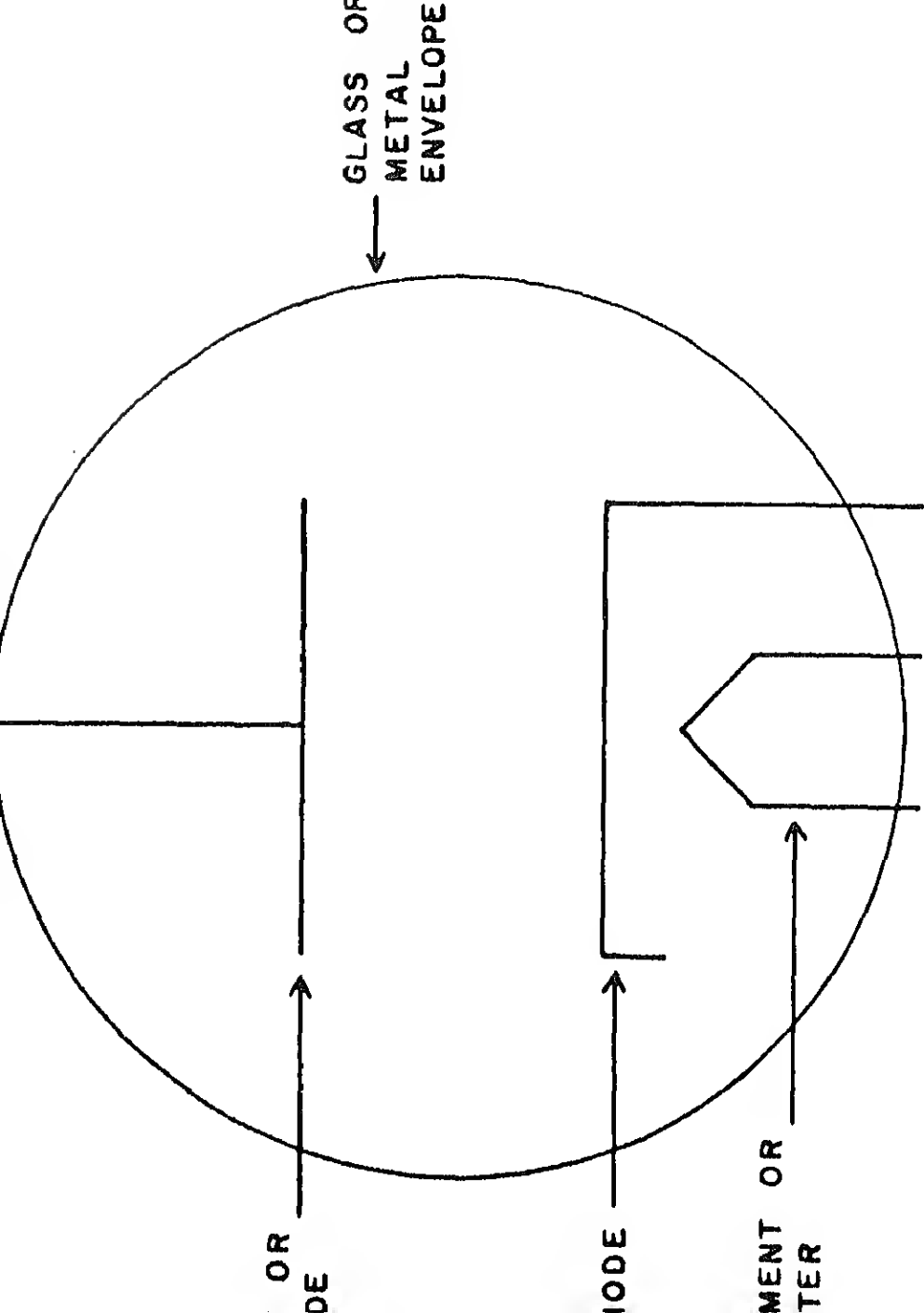


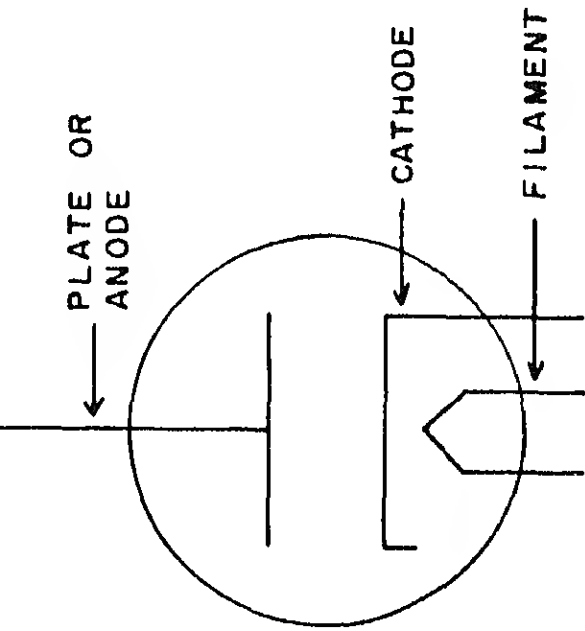


Circuit Analysis, Vol. I, NA 00-80-T-79, Chapter 4,
to 4-42.

TLINE

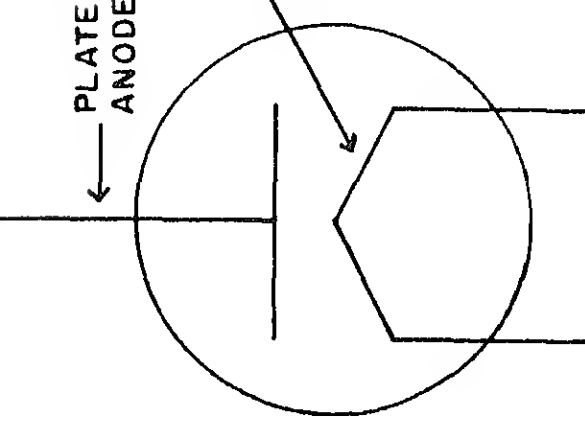
Construction of a Vacuum Tube.





INDIRECTLY HEATED CATHODE

Figure 3

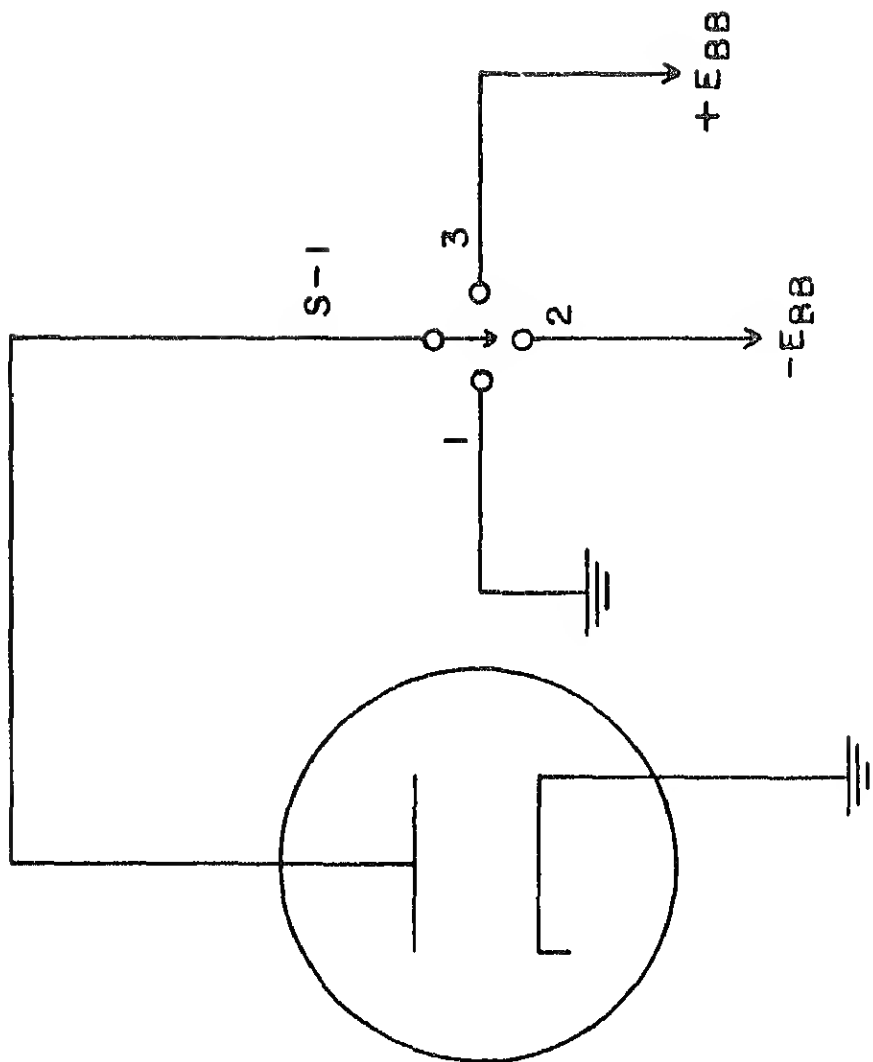


DIRECTLY HEATED CATHODE

Figure 2

B. Photoelectric emission

C. Cold cathode emission



uum Tube Circuit

. Shrader, Electronic Communication, Chapter 9, Fourth
1980, McGraw-Hill Book Company Inc.

OUTLINE

Construction of a Triode Vacuum Tube

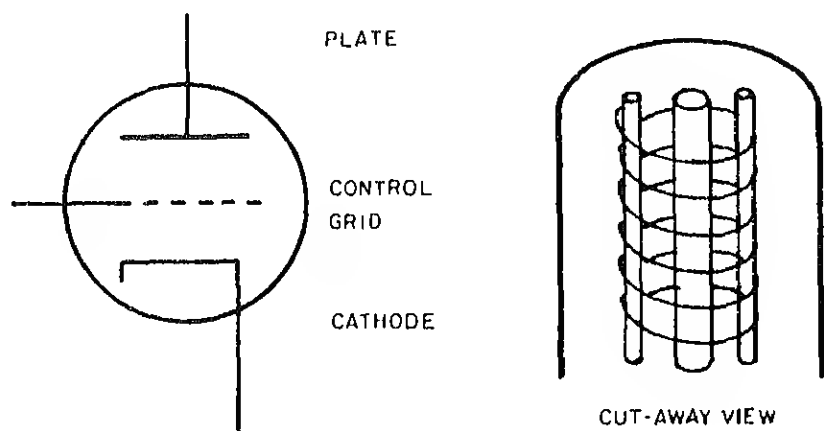
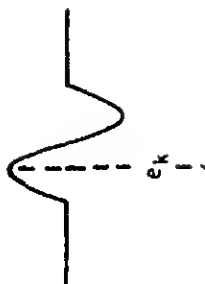
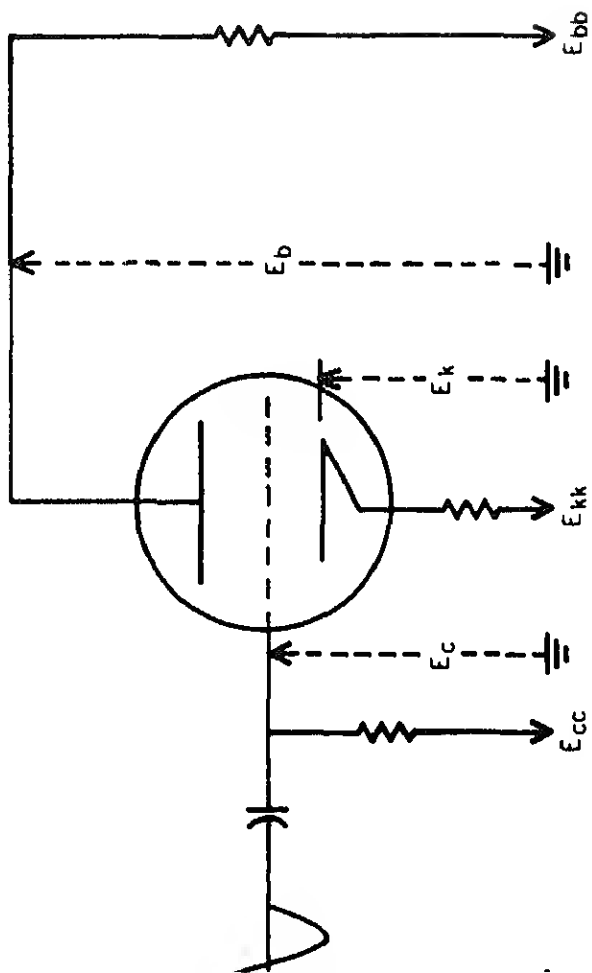
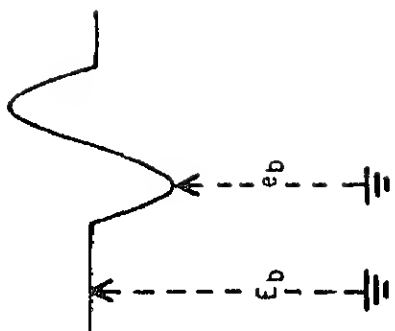


Figure 1 - Triode Vacuum Tube

II. Bias



Tube Notations

IV. Vacuum Tube Static Characteristic Curves

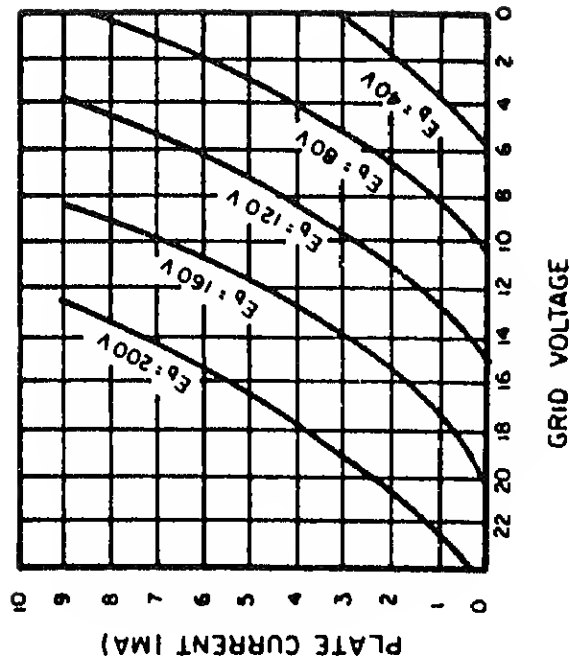
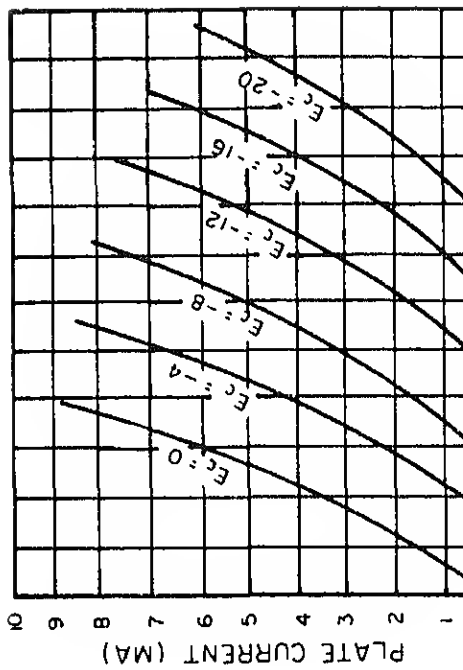


Figure 3 E_c - I_b GRID FAMILY OF CURVES



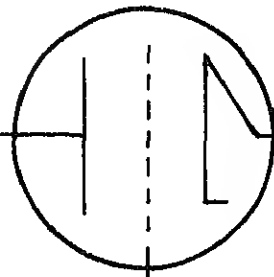
Characteristics of a Triode

$E_{B8} = 300V$

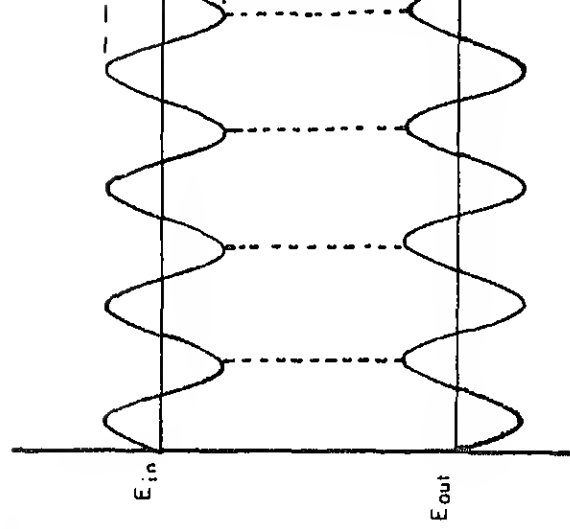
$R_L = 15K$

ASSUME 10 mA QUIESCENT TUBE CURRENT

OUTPUT



INPUT



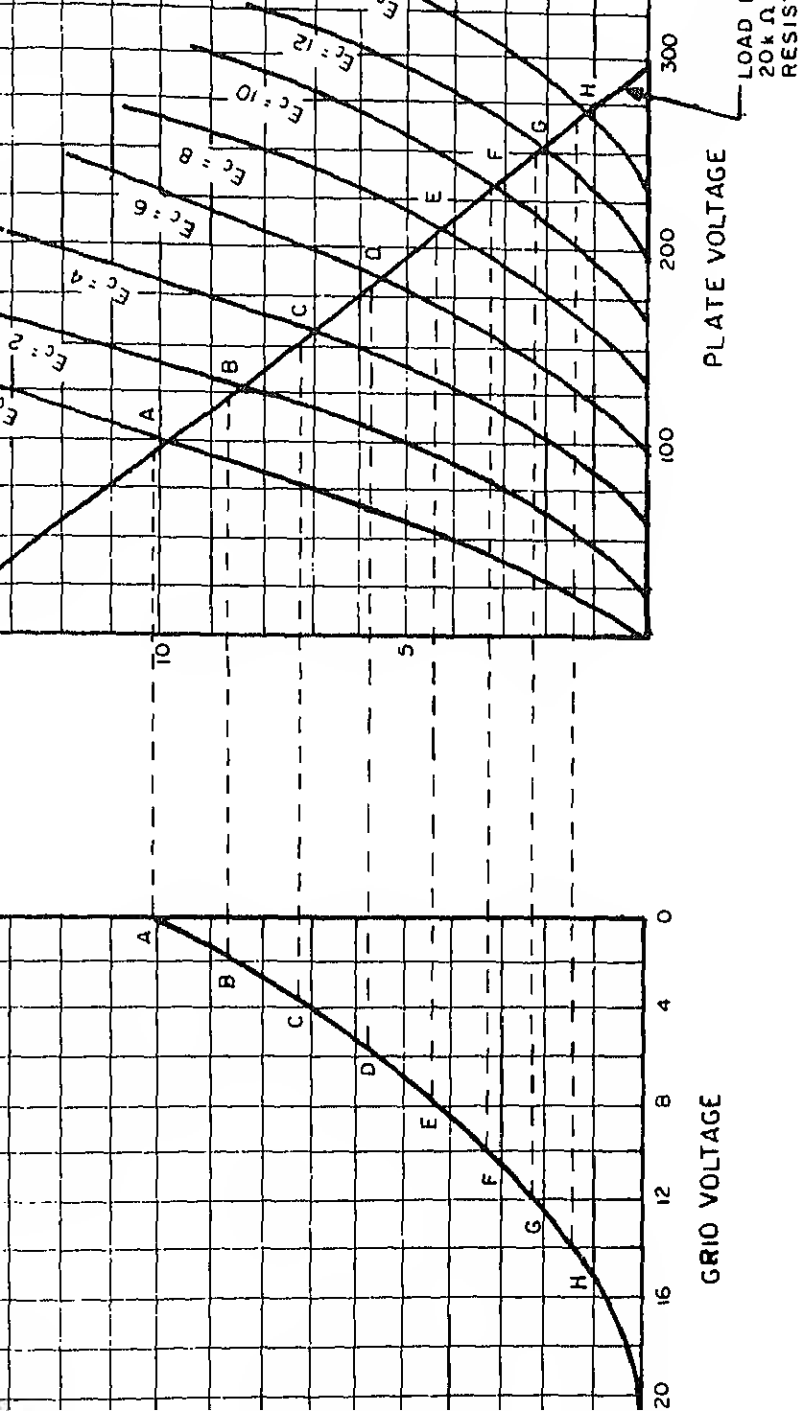
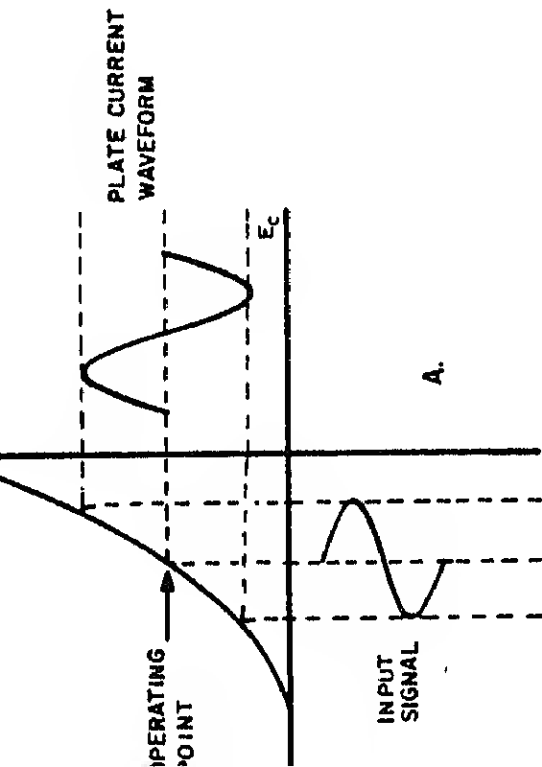
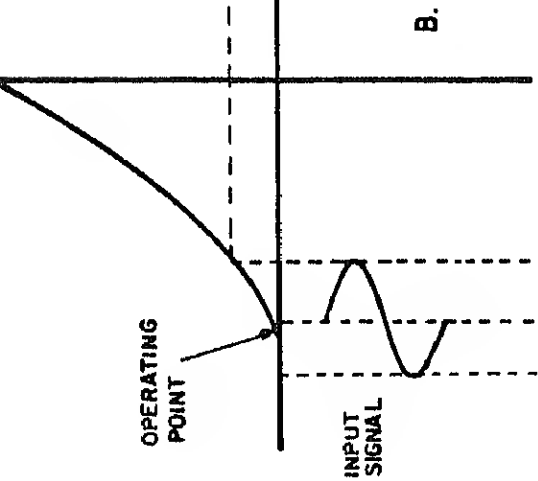


Figure 6 DYNAMIC TRANSFER CURVE (D.T.C.)

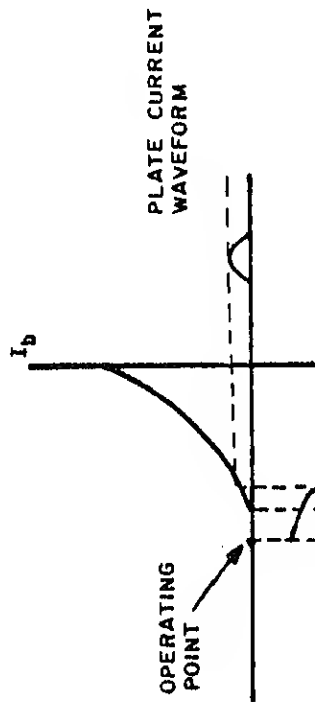
Dynamic Transfer Curve (DTC)



CLASS A OPERATION



CLASS B OPERATION



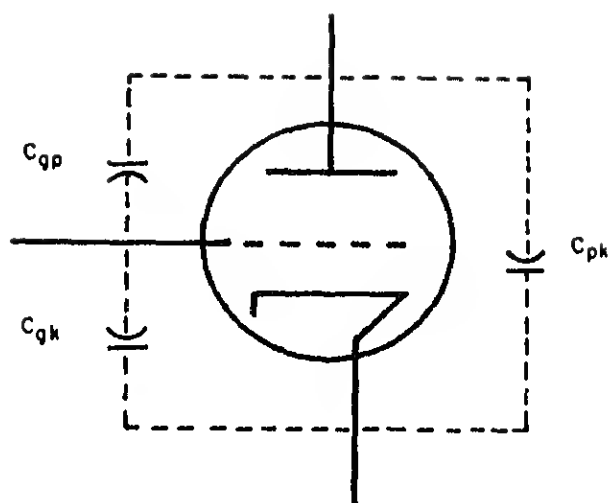


Figure 8 - Interelectrode Capacitance

Limitations of the Triode

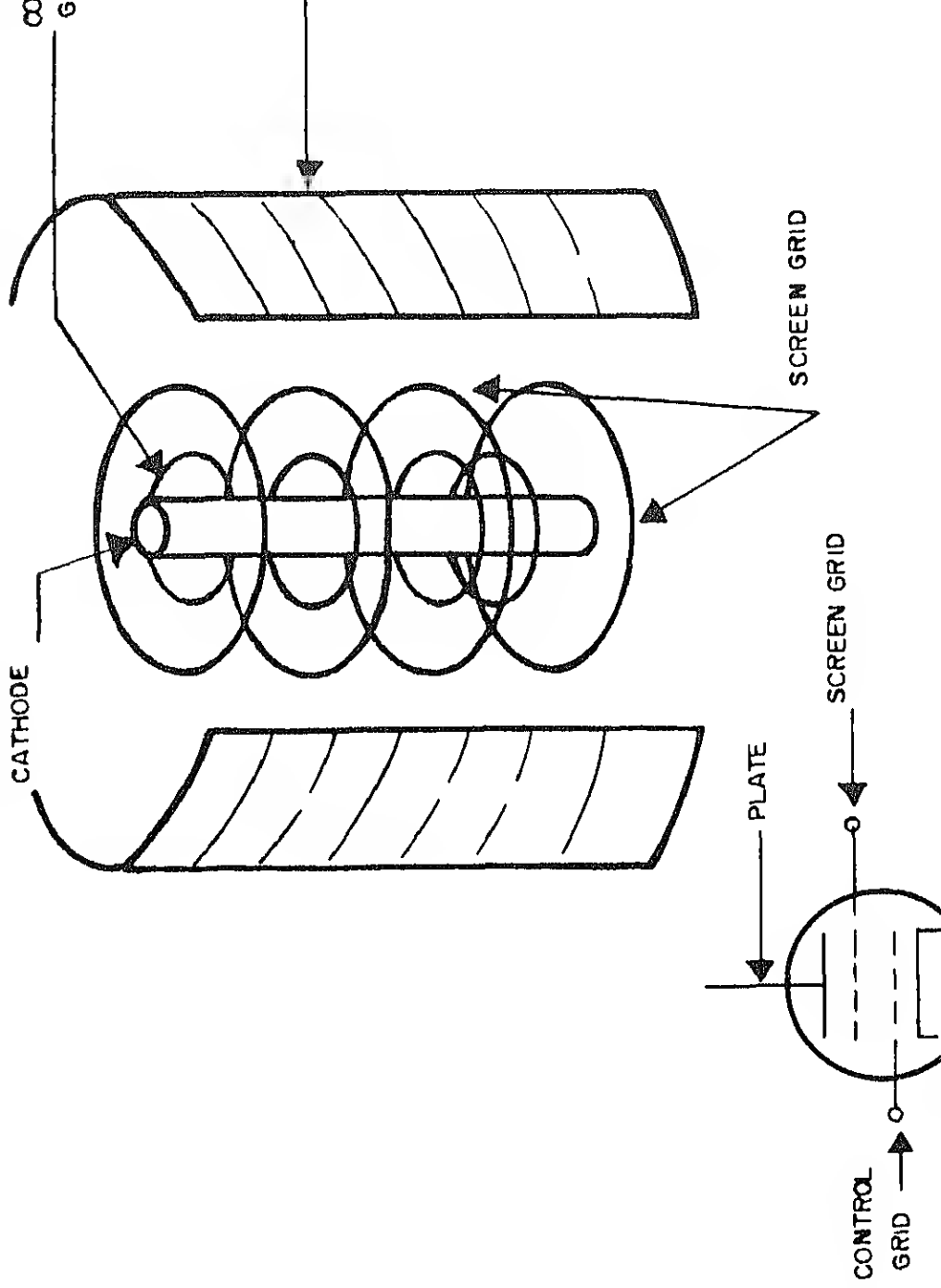
Electronic Circuit Analysis, Vol. I, NA 60-80-1-75, Chapter
1 to 172.

Electronics, Vol. I, NAVPERS 10087-C, Chapter 7, pages

W. Shrader, Electronic Communication, Chapter 9, Fourth
Edition, 1980, McGraw-Hill Book Company Inc.

OUTLINE:

codes



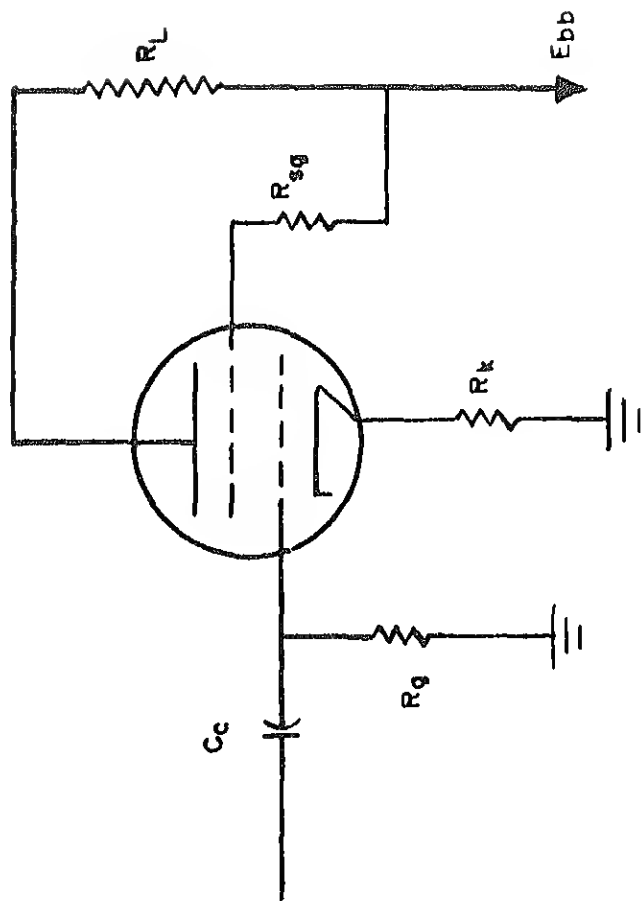
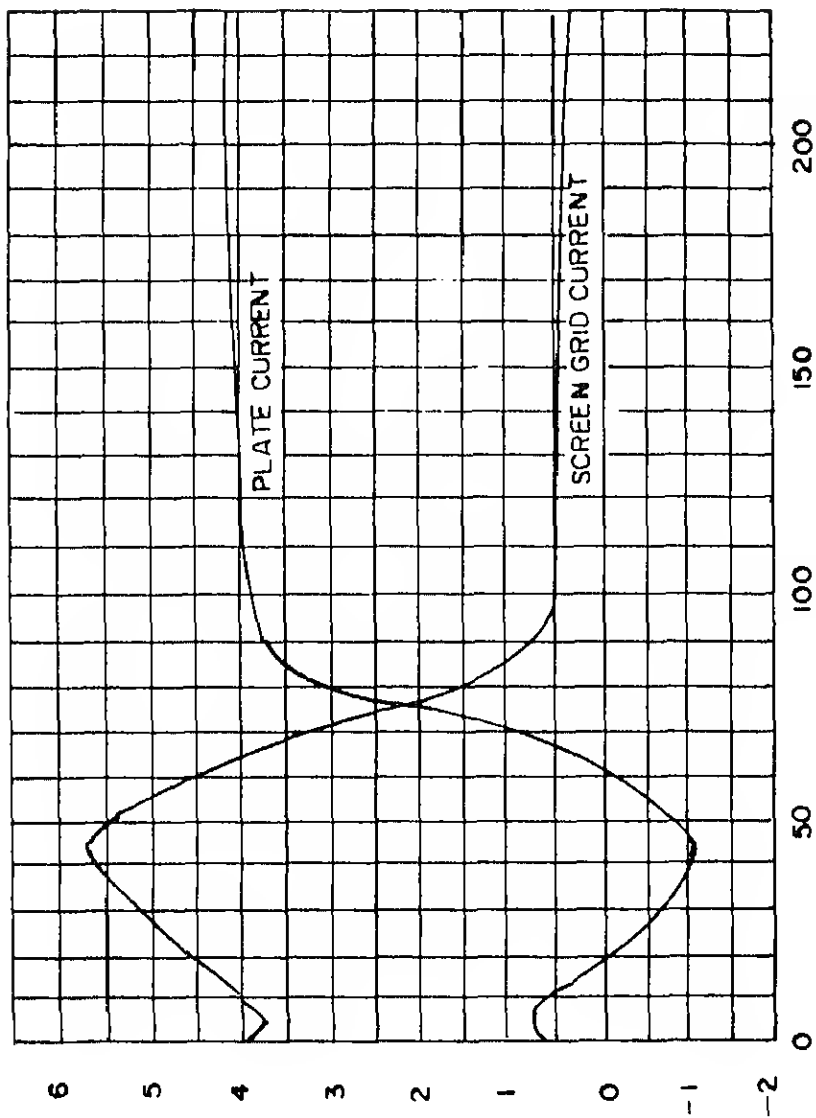


Figure 2 - TETRODE CIRCUIT

PLATE CURRENT AND SCREEN GRID CURRENT IN mA



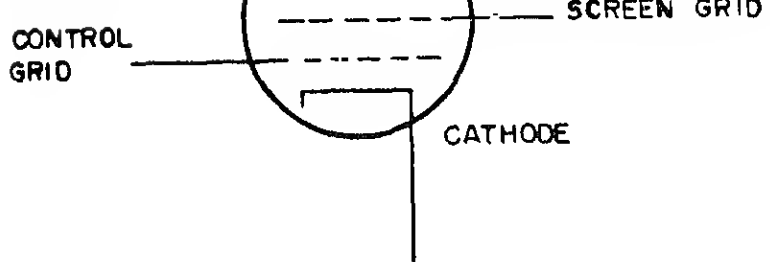


Figure 4 - PENTODE VACUUM TUBE

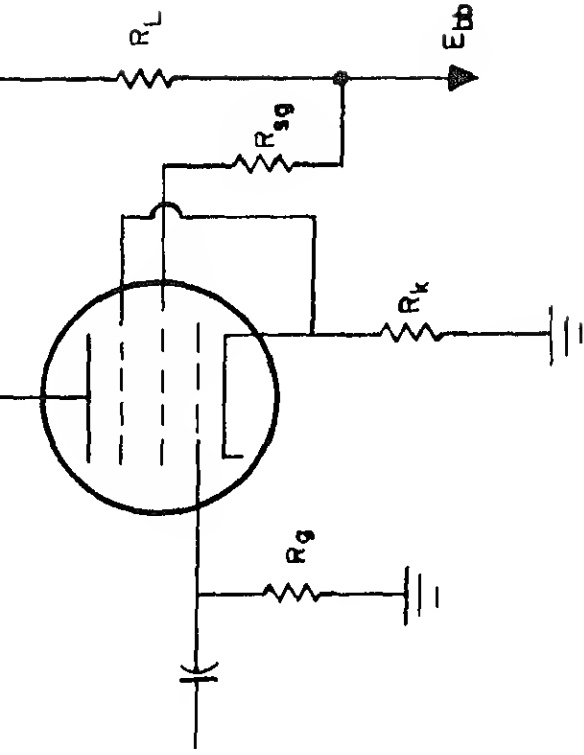
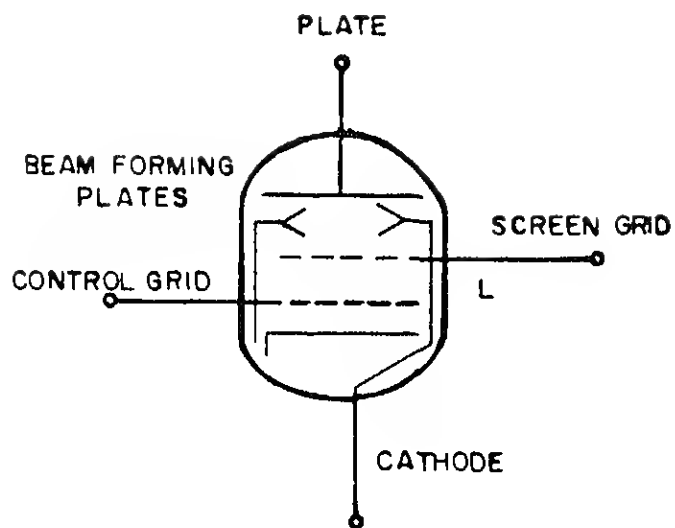


Figure 5 - PENTODE VACUUM TUBE CIRCUIT



ode-Ray Tubes

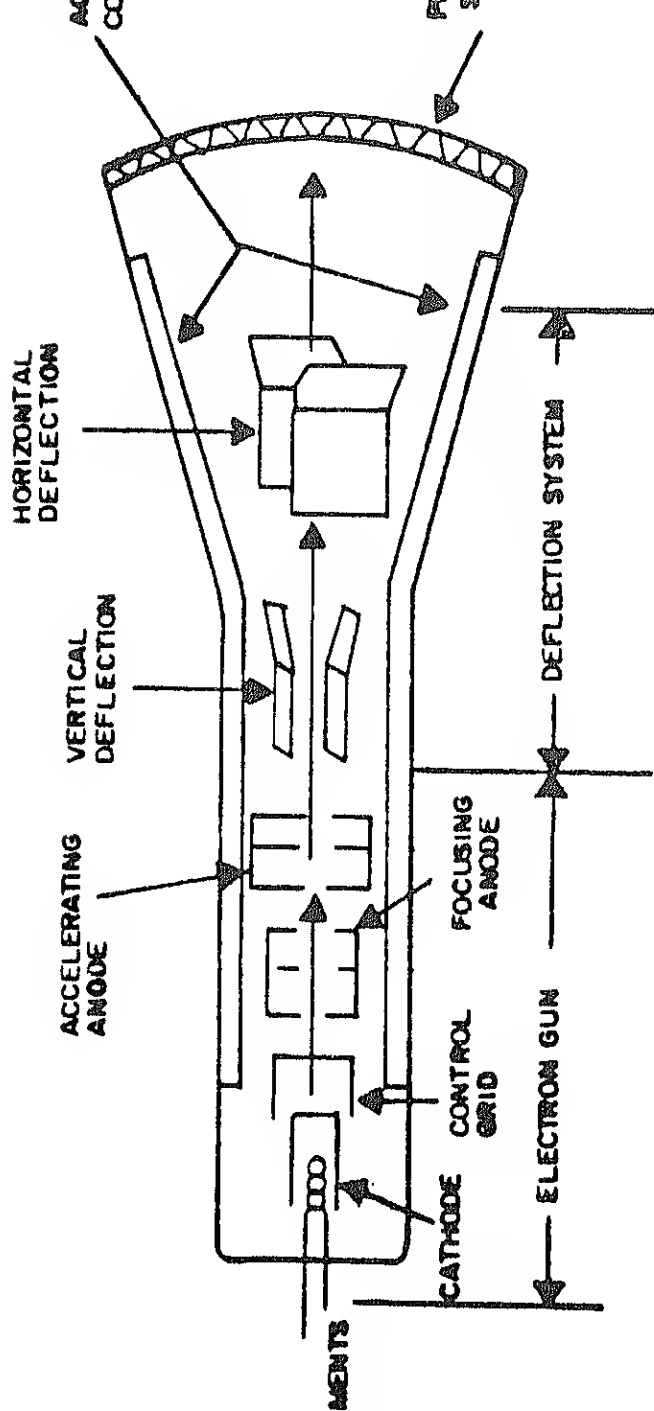


Figure 7 - CATHODE RAY TUBE

$$\frac{1}{2\pi fC}$$

ly

R

$$r_{EXC} = QEA$$

Only

$$\frac{Z_1 Z_2}{Z_1 + Z_2}$$

$$\frac{E_A}{I_{line}}$$

$$QX_L$$

$$Q^2 R$$

$$\left(\frac{X_L}{R}\right)^2$$

$$\frac{L}{RC}$$

$$= QI_{line}$$

$$P_a \cos \theta$$

$$\frac{P_t}{P_a} = \cos \theta$$

d Parallel

$$\frac{1}{2\pi\sqrt{LC}}$$

Q

$$4. \quad BW = \frac{R}{2\pi L}$$

$$5. \quad X_L = X_C = L/C$$

$$6. \quad F_O = \frac{X_L}{2\pi L}$$

Common Emitter Amplifier

$$1. \quad \beta = \frac{I_C}{I_B}$$

$$2. \quad \beta = \frac{\alpha}{1 - \alpha}$$

$$3. \quad I_{CEO} = I_{CBO}(\beta + 1)$$

$$4. \quad I_C = (\beta)(I_B) + (I_{CBO})(\beta + 1)$$

Common Base Amplifier

$$1. \quad = \frac{I_C}{I_E}$$

$$2. \quad = \frac{\beta}{\beta + 1}$$

Common Collector Amplifier

$$1. \quad \gamma = \frac{I_E}{I_B}$$

$$2. \quad \gamma = \beta + 1$$

$$dB = 20 \log(101) \frac{E_2}{E_1} \sqrt{\frac{Z_1}{Z_2}}$$

$$dB = 20 \log(101) \frac{I_2}{I_1} \sqrt{\frac{Z_2}{Z_1}}$$

Feedback Amplifiers

$$A_f = \frac{A_v}{1 - \beta A_v}$$

$$e_e = e_{in} + \beta e'_{out} = e_{in} + e_f$$

$$e'_{out} = \frac{A_v e_{in}}{1 - \beta A_v} = e_{in} A_f = e_e A_v$$

$$e_d' = \frac{e_d}{1 - \beta A_v}$$

$$\beta = \frac{R_1}{R_f + R_1} \quad \frac{R_E}{R_C}$$

Amps

$$E_{out} = (E_{in2} \frac{R_f}{R_{s2}}) + (-E_{in1} \frac{R_f}{R_{s1}})$$

$$E_{out} = e_{in} \frac{R_f}{R_s}$$